ANALYSIS OF ULTRA WIDE BAND (UWB)

TECHNOLOGY FOR AN INDOOR

GEOLOCATION AND PHYSIOLOGICAL

MONITORING SYSTEM

THESIS

Cengiz ALABACAK, 1stLt., TUAF

AFIT/GE/ENG/02M-01

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Report Documentation Page

Report Date 12 Mar 02	Report Type Final	Dates Covered (from... to) Jun 2001 - Mar 2002

Title and Subtitle Ultra Wide Band (UWB) Technology for an Indoor Geolocation and Physiological Monitoring System	Contract Number
	Grant Number
	Program Element Number
Author(s) 1st Lt Ceguiz Alabacak, TUAF	Project Number
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 P Street, Bldg 640 WPAFB, OH 45433-7665	Performing Organization Report Number AFIT/GE/ENG/02-01
Sponsoring/Monitoring Agency Name(s) and Address(es) DARPA Special Project Office Lt Col Gregory Vansuch 3701 N. Fairfax Drive Arlington VA 22203-1714	Sponsor/Monitor's Acronym(s)
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes
The original document contains color images.

Abstract
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Subject Terms
Ultra Wide Band (UWB), Pulse Position Modulation (PPM)

Report Classification unclassified	Classification of this page unclassified

Classification of Abstract	Limitation of Abstract
unclassified	UU
Number of Pages 90	

AFIT/GE/ENG/02M-01

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Cengiz Alabacak, BS

1st Lt., TUAF

Approved:

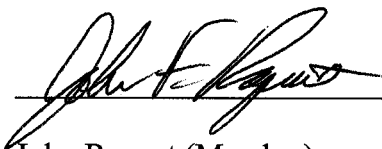_____   _11 March 2002_

Mikel M. Miller (Chairman)   date

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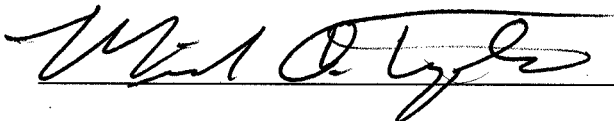John Raquet (Member)   date

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Michael A. Temple (Member)   date

AFIT/GE/ENG/02M-01

ANALYSIS OF ULTRA WIDE BAND (UWB) TECHNOLOGY FOR AN FOR

INDOOR GEOLOCATION AND PHYSIOLOGICAL MONITORING SYSTEM

THESIS

Presented to the Faculty

Department of Electrical and Computer Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Electrical Engineering

Cengiz Alabacak, BS

1stLt. TUAF

March 2002

Acknowledgments

I would like to begin by thanking AFIT/ENG for allowing me to conduct research in UWB technology. I would like to express my sincere appreciation to my faculty advisor, Lt. Col. Mikel M. Miller, and thesis committee member, Dr. Michael A. Temple, for their guidance and support throughout the course of this thesis effort.

I would like to give my regards to my fellow members of the Electrical Engineering Department in the Navigation, Controls, and Communication Sequences for their sense of humor, hard work, and dedication.

I would also like to thank my wife for her patience and support during my time here at AFIT.

Cengiz Alabacak

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Abstract

In dangerous or hostile situations it is important for command and control centers to know the location of each person in a building at all times. Examples are, a fire or a hostage situation where it is important to determine not only the location of a person in the building but also the physical situation of the person. Every year, nearly 100 firefighters die in the line of duty. A device that is capable of producing and sending geolocation information to a command and control center would offer a life-saving capability for those who risk their lives to save the lives of others. The United States Coast Guard Academy has been researching the development of an indoor, spread-spectrum geolocation system to track personnel inside buildings under a project funded by the Defense Advanced Research Projects Agency (DARPA) Small Unit Operations Geolocation program. As a result, the determination of the location of the personnel in the building was achieved within a 2.86-meter radius. In other research the effort was to develop a system that will track individuals inside buildings to an accuracy of less than one meter. Four methods were evaluated to determine the position of a transmitter: multitones, AM with 3.2 MHz modulation, single carrier, and spread spectrum. Of these four methods, spread spectrum was the only one that showed some promise of obtaining the desired accuracy. The other three failed due to multipath problems.

This research analyzes and characterizes the Ultra Wide Band (UWB) signal in the various operational environments associated with indoor geolocation. Additionally, "typical usage scenarios" for the interaction between UWB and other devices are also tested and evaluated.

ULTRA WIDE BAND (UWB) TECHNOLOGY FOR AN FOR INDOOR GEOLOCATION AND PHYSIOLOGICAL MONITORING SYSTEM

I.   INTRODUCTION

1.1   BACKGROUND/MOTIVATION

Every year, nearly 100 firefighters die in the line of duty. A device that is capable of producing and sending geolocation information to a command and control center would offer a life-saving capability for those who risk their lives to save the lives of others. Services like 911 (E-911) will permit a mobile telephone user to be located within 50 m when a call is placed to the emergency number [1]. In commercial applications, more precise indoor geolocation technology will have the ability to:

1. Track the elderly or children who are away from supervision.

2. Locate portable equipment in hospitals.

3. Provide information to track prison inmates.

4. Provide navigation for the blind and other handicapped people.

5. Provide navigation for police, fire fighters, and soldiers to safely complete rescue operations inside buildings.

The Global Positioning System (GPS), a space-based radio navigation system, does not work well in indoor environments. Thus, due to the system's low received

power, there is a need for new and innovative signal processing and locating algorithms to provide indoor navigation. In dangerous or hostile situations, it is important for command and control centers to know each person's position and physiological status in a building at all times. For example, in a fire or hostage situation, it is vital to determine not only a person's location in the building but also the physical condition of the person. So the desired system/monitor would need to include additional sensors such as:

1. Electrocardiography (ECG).

2. Skin Temperature.

3. Pulse Oximetry Environmental.

4. Environmental Carbon Dioxide (CO_2).

5. Galvanic Skin Response (GSR).

1.2 PROBLEM STATEMENT

Conventional radio technology accomplishes information transfer by modulating data onto carrier waves. Continuous carrier sine waves are transmitted with information embedded as modulation of the wave's amplitude or frequency. This technology is approaching its limit in its ability to improve bandwidth (amount of information sent) and channelization (number of users). Increasing the absolute bandwidth necessitates using higher carrier frequencies, while relative bandwidth must be kept low [2].

Indoor geolocation faces additional difficulties as compared to outdoor geolocation. Attenuation and multipath reflections of the line-of-sight (LOS) signal (or direct path) by the walls, floors, and ceiling of a building are the main factors preventing typical GPS receivers from functioning indoors. Most of the time, the sum of multipath

signals is stronger than the direct path signal, thereby preventing the receiver from accurately calculating the time of arrival (TOA). The multipath signal distorts the cross correlation function peak, as detected by a receiver in its tracking loops, thus preventing receiver "lock"[3].

According to Shannon's famous 1948 paper, the signal, when corrupted by white Gaussian noise, should statistically appear as Gaussian noise and be as wideband as possible to achieve maximum performance [4]. Based on this idea, a new technology called "ultra wide band (UWB)", provides a possible solution to the problems encountered in indoor environments.

1.3   SUMMARY OF CURRENT KNOWLEDGE

The United States Coast Guard Academy (USCGA) accomplished preliminary research into the development of an indoor, spread spectrum geolocation system to track personnel inside buildings under a project funded by the Defense Advanced Research Project Agency (DARPA) called the Small Unit Operations Geolocation program. The system accomplished personal location determination in a building within a 2.86-meter radius [3].

In other research funded by DARPA, effort was made to develop a system for tracking individuals inside buildings within an accuracy of less than one meter. From September 1996 to April 1997, four methods were evaluated to determine the position of a transmitter: "multitones," "amplitude modulation (am) with 3.2 MHz modulation," "single carrier," and "spread spectrum." Of these four methods, spread spectrum was the only one that showed promise for obtaining the desired accuracy. The other three

methods failed due to multipath problems. Even when using spread spectrum techniques to measure signal TOA, the obtained accuracy did not meet the requirements [5].

On the other hand, UWB technology, the promising solution to many propagation problems, has attracted the attention of many civilian companies. Since there are numerous application areas in which UWB can provide significant performance and cost advantages, UWB technology has become the main focus of many companies working in the development of systems for communications, radar and geopositioning.

With its patented UWB receiver technology, Multi Spectral Solution Inc. (MSSI) has demonstrated the ability to detect single pulses of UWB energy with extremely high sensitivity and in the presence of high interference and in-band interferers. A single-pulse detection capability is critical for high-speed (multiple Mega-bits/second), mobile wireless applications. Single-pulse detection also allows for a significant reduction in transmitted power, with resultant reduction in interference potential to other systems. The properties of MSSI's detector also include the ability to respond to the leading edge of a UWB pulse, enabling applications for precision positioning and geolocation for in-building, high multipath environments [6].

Aether Wire Inc. has developed a position location and communication system that overcomes the limitations making other location systems unsuitable for most imagined applications. Other localization systems give absolute position on the geoid *(e.g., GPS)*, location relative to fixed beacons *(e.g.* LORAN), or location relative to a starting point *(e.g.,* inertial platforms). Aether Wire's system provides relative position location within a network of RF transceivers (localizers) distributed throughout the environment. It is estimated that this technology will be capable of localization to

centimeter accuracy levels over *kilometer* distances. Unlike GPS, this system will operate within buildings, urban areas, or forests. Also, these localizers inherently share position location information throughout the network, while most other localization systems require a separate communication channel. The most significant aspect of Æther Wire's technology is that localizers can be totally integrated in low-cost CMOS circuits [7].

Time Domain®'s PulsON® technology has the ability to fuse wireless communication, tracking and radar capabilities into a single chipset. It is offered as the optimal technology for a wide array of applications including wireless networks, public safety applications involving motion detection through walls or rubble, personnel and asset tracking in-building, invisible security domes and fences, and ultra high precision positioning/tracking systems [8].

Time Domain Inc. has developed the PulsON® Chipset control and exploit the power of UWB technology. The advantages of the PulsON® technology can be listed as:

1. Extremely low power

2. Spectral efficiency

3. Multi-Channel capability with immunity to interference

4. Excellent wall penetration characteristics

5. **5.** Low cost

1.4 SCOPE

Since this is AFIT's first investigation into exploitating of UWB technology, the main focus of the research is to analyze and characterize the UWB signal in the various operational environments associated with indoor geolocation. For this purpose, UWB performance in an interference environment is evaluated. Additionally, "typical usage scenarios" for the interaction between UWB and other devices is tested and evaluated.

1.5 APPROACH

The goal of this research is to analyze the utility of UWB for indoor geolocation and to evaluate a prototype system, which will send information detailing a person's position and physiological status to a command center. In a real world environment, geolocation and physiological status information needs to be sent to a command and control center that may be located several miles away from the operational environment. However, given the current UWB status (presented in Chapter 2) and the equipment technology capability, this research is conducted in a smaller indoor range.

1.6 MATERIALS AND EQUIPMENT

PulsON® Application Demonstrator (PAD) is the primary hardware used to test the UWB technology performance for our applications in different environments. These PADs have been developed by Time Domain Corporation based on the Time Modulated Ultra Wideband (TM-UWB) architecture. By using PADs, one has the ability to transmit/receive pulse trains of individual ultra-wideband 'pulses' at very precise time

intervals. Detailed information about the equipment and its capabilities are presented in Chapter 2.

1.7   *THESIS ORGANIZATION*

Chapter 2 presents background information about UWB, TM-UWM, and current status of UWB.   Chapter 3 discusses the UWB test equipment, the setup and tests conducted.   A detailed analysis of the test results is provided in Chapter 4. Chapter 5 offers conclusions and recommendations for future research.

II.   UWB CHARACTERTERISTICS

2.1   INTRODUCTION

UWB technology has been around since the 1980s, and has been mainly used for radar-based applications [9]. However thanks to the wideband nature of the signal, very accurate timing information is available. Additionally, due to recent developments, UWB technology has also been of considerable interest in communication and radar applications demanding low probability of intercept (LPI) and detection (LPD), multipath immunity, high data throughput, precision ranging and localization.

Multipath propagation is one of the most significant obstacles when Radio Frequency (RF) techniques are used indoors. Since UWB waveforms are of such short time duration, they are relatively immune to multipath degradation effects as observed in mobile and in-building environments. Thus, UWB has gained recent attention and has been identified as a possible solution to a wide range of RF problems. For example, in communication systems, UWB pulses can be used to provide extremely high data rate performance in multi-user network applications. Additionally, in radar applications, UWB can provide very fine range resolution and precision distance and/or positioning measurement capabilities. Some UWB applications can co-exist with narrowband services over the same frequency band because of the low spectral density of UWB waveforms [6].

The purpose of this chapter is to review the literature concerning UWB, TM-UWM, and current status of UWB.

2.2 DESCRIPTION OF UWB TECHNOLOGY

UWB signals can be defined as signals having a fractional bandwidth of at least 25% of the center frequency or those occupying 1.5 GHz or more of the spectrum. Fractional bandwidth B_f is defined as [9,10]:

$$B_f = 2\frac{f_h - f_l}{f_h + f_l}$$

(1)

where

B_f = Fractional bandwidth (Hertz)

f_h = The highest -10dB frequency point of the signal spectrum (Hertz)

f_l = The lowest −10dB frequency point of the signal spectrum (Hertz)

UWB is a wireless technology for transmitting digital data over a wide spectrum with very low power and has the ability to carry huge amounts of data over short distances at very low power. In addition, UWB has the ability to carry signals through doors and other obstacles. Instead of traditional carrier wave modulation, UWB transmitters broadcast digital pulses that are precisely timed on a signal spread across a wide spectrum. The transmitter and receiver must be synchronized to send and receive pulses with accuracies approaching trillionths of a second.

The basic concept is to develop, transmit and receive an extremely short duration burst of RF energy, typically a few tens of picoseconds (trillionths of a second) to a few

nanoseconds (billionths of a second) in duration. The UWB advantage rests in its ability to spread the signal energy across a wide bandwidth.

2.3   HISTORY OF UWB

The history of interest in UWB dates back to the 1960´s. Terms used for the concept were "nonsinusoidal," "baseband," "impulse radio," and "carrier free signals." Dr. Gerald F. Ross first demonstrated the feasibility of utilizing UWB waveforms for radar and communications applications in the late 1960's and early 1970's. In the early 1960´s Ross developed time-domain electromagnetics.   The work was a result of trying to find better tools to analyze the general microwave 2-N port [6]. The term "UWB" was not adopted until approximately 1989. Harmuth conducted other revolutionary work in the late 1960´s [2,11-17]. Eventually, hardware like the avalanche transistor and tunnel diode made implementations possible. The advent of the sampling oscilloscope further aided in system development. During the 1970´s, evolution and research into UWB often focused towards radar systems, which needed to be enhanced with better resolution [18-27]. This demand required wider bandwidth. At this time extensive research was conducted in the former Soviet Union by researchers like Astanin, and in China as well [28]. Taylor has published some public material based on research in the United States from this period [9]. In 1978, Bennett and Ross wrote a summary of time-domain electromagnetics [29].   At about this time, efforts using carrier-free radio for communication purposes were started. During the last decade, the military has begun to support initiatives for developing commercial applications.   These commercial applications, and the evolution of increasingly faster digital circuits, have led to the

development of inexpensive hardware. The possibility of producing low cost units, and unlicensed use, has recently boosted the interest in UWB.

2.4   OBJECTIVES FOR USING UWB

There are several favorable properties associated with UWB techniques. Depending on the type of applications considered, different objectives can be identified.

2.4.1   EVOLVING NEED FOR HIGHER BIT RATES

The demand for broadband services is rapidly increasing. Most of the evolving new services require high data rates. To transmit higher data rates, more bandwidth is required and the need for increased information bandwidth is expected to grow exponentially. Depending on practical considerations, the carrier frequency must be chosen relatively high to accommodate the bandwidth expansion. Narrowband systems can be defined as systems having less than 1% (0.01) fractional bandwidth [9]. In addition, associated antennas, resonators, and other components operate over relatively small bandwidths. Using sinusoidal carrier frequencies eventually forces the carrier into spectral regions where atmospheric absorption is considerably high. As an example, consider a digital radio system designed for a data rate of 100 Mbps. Depending on the modulation used, the required transmission bandwidth may be as high as 200 MHz. To keep the relative bandwidth under 0.01 of the center frequency, the carrier frequency would have to be more than 2 GHz. For a 100 times higher data rate, using the same requirement on relative bandwidth, the required carrier frequency would exceed 200

GHz. With the use of UWB, the low relative bandwidth constraint is removed and higher

bit rates may be achieved without moving to higher frequency regions.

2.4.2   *LARGE BANDWIDTH – HIGH RESOLUTION*

Achieving high resolution is of primary importance in radar and geolocation

applications. Distance can be determined by measuring the time delay of a pulse as it

traverses the channel. The *uncertainty* of the measurement is proportional to the pulse

rise time, which is inversely proportional to the pulse bandwidth. Figure 1 shows unity-

amplitude Gaussian monopulse with center frequency 2 GHz sampled at a rate of 100

GHz.

$$\Delta t \cong \frac{1}{W} = tr \tag{2}$$

where

Δt =   Measurement the uncertainty (Sec)

t_r =   Rise Time (Sec)

W   =   Signal Bandwidth (Hertz)
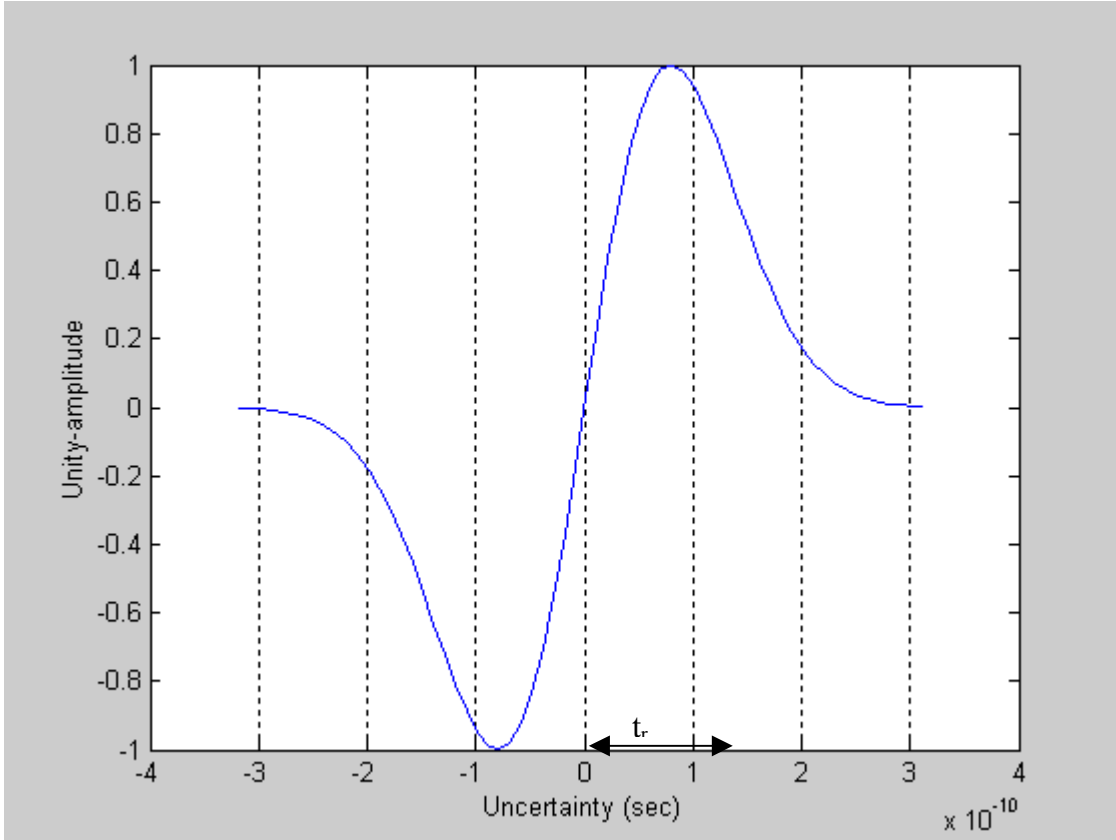
Figure 1

The larger the bandwidth, the more precisely one can measure range. As seen from Equation (2), it is obvious that a narrow time-domain pulse results in a wide spectrum in the frequency-domain. Additionally, the inverse of the bandwidth is proportional to achieved resolution.

2.4.3 LARGE BANDWIDTH HIGH MULTIPATH RESISTANCE

UWB systems are particularly well suited for high-speed, mobile wireless applications. Also, because of the extremely short duration waveforms, packet burst and time division multiple access (TDMA) protocols for multi-user communications are readily implemented [6]. In addition, UWB waveforms are relatively immune to

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multipath cancellation effects as observed in mobile and in-building environments. Multipath cancellation occurs when a strong reflected wave, e.g., off a wall, ceiling, vehicle, building, etc., arrives partially or totally out-of-phase with the direct path signal, causing a reduced amplitude response in the receiver.

Multipath cancellation is a key-limiting factor in the performance of wireless systems in enclosed spaces. Metallic enclosures and objects accentuate the multipath problems. Received signals can be severely attenuated due to out-of-phase reflections from the surrounding surfaces and other objects interfering with the direct path [30].

Because of its extremely fast response time, the UWB detector responds to this return and ignores or gates out the residue. For a spread spectrum waveform, these inappropriate returns fall directly on top of successive chips, thereby severely limiting system performance [8].

2.4.4   LOW FREQUENCY GOOD PENETRATION PROPERTIES

Electromagnetic theory suggests that lower frequencies have better penetrating properties. The possibility of using a large spectrum in combination with lower frequencies results in desirable properties. UWB has thus been studied and is being used for applications like ground penetrating radar, foliage penetrating radar [31] and short-range radar to detect hidden objects behind walls. This penetration property is also of great importance for indoor geolocation systems.

2.4.5   COVERT RADIO LPI/LPD

UWB effectively spreads the energy over a large spectral region and has a low power spectral density (watts/hertz). This results in LPD and LPI waveforms. Thus, UWB is highly useful for military applications requiring covert communication in hostile environments. Also, it is relatively insensitive to intentional jamming [8].

2.4.6   CROWDED SPECTRUM

The low energy density implies possible use on an unlicensed basis. The Federal Communications Commission (FCC), which decides regulatory issues in the US market, is now considering this issue. The transmitted signal appears noise-like, and overlay schemes could be used without interfering with existing narrowband radio systems [6].

2.4.7   IMPLEMENTATION COST

Since the UWB technique can be carrier-free, its transceivers can be inexpensively produced using Complementary Metal Oxide Semiconductor (CMOS) technology, instead of the more expensive GaAs Monolithic Microwave Integrated Circuit (MMIC) technology. Automotive collision avoidance systems, sensor airbags and liquid level are only some examples of proposed implementations. UWB advocates claim the corresponding cost for UWB circuits will be less than $1 [6].

2.5   REGULATORY ISSUES

FCC is in the process of determining the legality of UWB transmissions [32]. Due to the wideband nature of UWB emissions, it could potentially interfere with other

licensed bands in the frequency domain if left unregulated [33]. The FCC's responsibility is to satisfy the need for more efficient methods of utilizing the available spectrum, as represented by UWB, without causing interference to those currently occupying the spectrum. The FCC is currently working on setting emissions limits that would allow UWB communication systems to be deployed on an unlicensed basis following the Part 15.209 rules for radiated emission of intentional radiators, the same rules governing radiated emissions from home computers, for example. This rule change would allow UWB-enabled devices to overlay with existing narrowband systems, which is currently not allowed, and result in a much more efficient use of the available spectrum. The FCC has studied the topic of UWB and released, in August 1998, a Notice of Inquiry (NOI) [34] to "investigate the possibility of permitting the operation of ultra wideband radio systems on an unlicensed basis under part 15 of its rules." Part 15 regulates the emission from unlicensed intentional radiators and unlicensed unintentional radiators like PCs and other digital devices. It is divided in two classes, A and B, depending on the environment. Class A explains the limits related to digital devices that are marketed for use in commercial and industrial environments. The more restrictive class B explains the limits related to devices used in residential environments, as well as, commercial and industrial environments. These emission limits are defined in terms of microvolts per meter (uV/m), representing the electric field strength of the radiator. To express this in terms of radiated power the following formula can be used. The radiated power, P, from an emitter is given by [34]:

$$P = E_0^2 \, 4\pi R^2 / \eta \qquad\qquad (3)$$

where

E_0 =   Electric field strength (V/m)

R   =   Radius of the sphere (meters)

η =   Characteristic impedance of vacuum ($377\,\Omega$)

The FCC Part 15.209 rules limit the emissions for intentional radiators to 500 uV/m measured at a distance of 3 meters in a 1MHz bandwidth for frequencies greater than 960MHz. This corresponds to an emitted power spectral density of -41.3dBm/MHz. Levels for class A and B under part 15 are given in Table 1.

Table 1 Part 15 Class A and B Limits

CLASS	LIMITS (mV/m)
A	300@10m
B	500@3m

For example, consider a UWB system having 1 W peak power, a 2 ns pulse width and 128 kbps data rate. With an obtained bandwidth of 500 MHz, the peak power density is only 2 nW/Hz, with an average power density of 0.5 pW/Hz [35].

Figure 2 below shows how the current Notice of Rule Making (NPRM) rules would limit UWB transmitted power spectral density for frequencies greater than 2GHz.
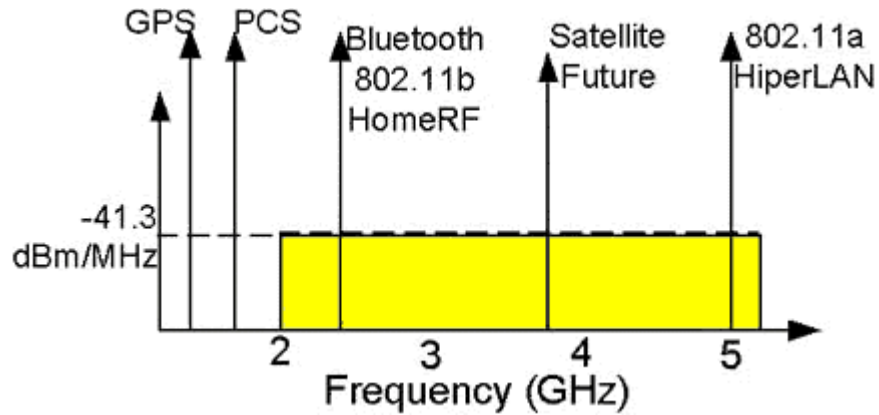
Figure 2 Power spectral density limits in current NPRM [6]

The FCC is considering even lower spectral density limits below 2GHz in order to protect the critical GPS signal even more, but currently no upper boundary has been defined. Results of a National Telecommunications and Information Administration (NTIA) report analyzing the impact of UWB emissions on GPS, which operate at 1.2 and 1.5GHz, was recently published and suggests that an additional 20-35dB greater attenuation, beyond the power limits described in the FCC Part 15.209, may be needed to protect the GPS band [36].

There are many factors affecting how UWB impacts other "narrowband" systems, including spatial separation between devices, channel propagation losses, modulation techniques, the UWB Pulse Repetition Frequency (PRF), and the "narrowband" receiver antenna gain in the direction of the UWB transmitter [33-34,36-37]. For example, a UWB system that sends impulses at a constant rate (PRF) with no modulation causes spikes in the frequency domain that are separated by the PRF. Adding either amplitude modulation or time dithering (i.e., slightly changing the time the impulses are transmitted) results in spreading the spectrum of the UWB emission to look more flat. As

a result, the interference caused by a UWB transmitter can be viewed as a wideband interferer, and it has the effect of raising the noise floor of a "narrowband" receiver.

There are three main points to consider when looking at wideband interference [34,38,39]. First, if UWB complies with the Part 15 power spectral density requirements, its emissions are no worse than other devices regulated by this same standard, including computers and other electronic devices. Second, interference studies need to consider "typical usage scenarios" for the interaction between UWB and other devices. Third, FCC restrictions are only a beginning. Further coordination through standards participation may be necessary to come up with coexistence methods for operational scenarios that are important for the industry. For example, if UWB is to be used as Personal Area Network (PAN) technology in close proximity to an 802.11a Local Area Network (LAN), then the UWB system must be designed in such a manner as to peacefully coexist with the LAN. This can be achieved through industry involvement and standards participation, as well as, by careful design.

Figure 2 illustrates two other important considerations for UWB systems. First, UWB emissions will be allowed only at a much lower transmit power spectral density compared to other "narrowband" services. This low power can be seen as both a limitation and a benefit. It restricts UWB emissions to relatively short distances, but results in a very power-efficient and low-cost implementation, which preserves battery life. Second, Figure 2 also shows that UWB systems will most likely suffer from interference from other "narrowband" users. These interferers should be suppressed by using some form of adaptive interference suppression technique, which is a focus in research.

The first FCC report and order permitting the marketing and operation of certain types of new products incorporating UWB technology come on 14 February 2002 [8]. Under the new rules, UWB communications devices will be restricted to intentional operation only between 3.1 and 10.6 GHz; through-wall imaging and surveillance systems restricted between 1.99 and 10.6 GHz (and used only for law enforcement, fire and rescue, and other designated organizations) and automotive radars restricted to frequencies above 24.075 GHz.

2.6 **TM-UWB IN MORE DETAIL**

Sinusoidal based functions and Fourier transforms are common in radio transmission discussions, since terms are expressed in frequency and phase. In addition, with the advent of resonators, often contributed to Marconi, the focus changed from radio to sinusoidal waves [9]. From that time, radio has been treated in terms of frequency and the medium has been divided into channels using specific frequency bands allowing many contemporary users. This method of channelizing is called Frequency Division Multiple Access (FDMA). Using the transit time of a signal to calculate distance requires an accurate measurement of signal time of arrival. The more sharply defined a signal is in time, the more spread out the signal is in the frequency domain. This is true for nonsinusoidal impulses, as well as for the pulse-modulated sinewaves used in conventional radar. TM-UWB utilizes very short pulses sent with relatively long intervals and is sometimes referred to as impulse radio. As seen in Equation 4 below, the narrower the pulse, the wider the bandwidth.

$$x(at) \xrightarrow{\quad F \quad} \frac{1}{|a|} X\left(\frac{w}{a}\right) \qquad\qquad 4)$$

where

$$x(at) \quad = \quad \text{Signal in time domain}$$

$$X\left(\frac{w}{a}\right) \quad = \quad \text{Signal in frequency domain (Radius)}$$

$$w \quad = \quad 2\pi f$$

$$a \quad = \quad \text{Arbitrary signal amplitude}$$

where

$$f \quad = \quad \text{Frequency (Hertz)}$$

TM-UWB can be thought of as a combination of Time Division Multiple Access (TDMA) and code Division Multiple Access (CDMA) [40]. However, the users are not synchronized in time and are separated by orthogonal, or near orthogonal, codes. The relation between time and frequency is illustrated in Equation (4) and also shown in Figure 3 and Figure 4. Figure 3 is the frequency response and Figure 4 is the transient data from which it is derived. From Fourier analysis, high frequency signals are concentrated in short time intervals in the time domain; low frequency signals are concentrated at longer time durations in the time domain. A shift from long to short time durations in the time domain results in a shift from low to high frequencies in the frequency domain, and vice-versa.
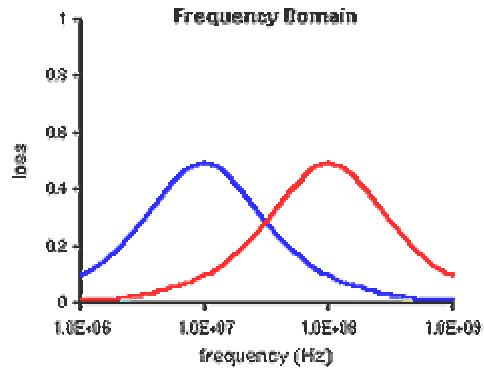
Figure 3 Frequency Domain [41]
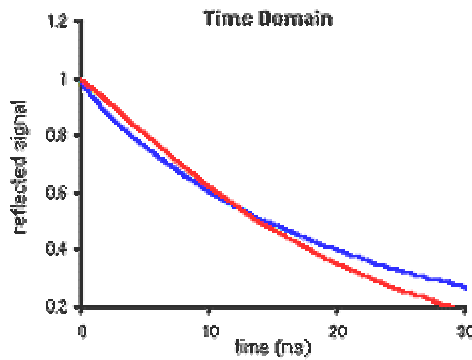
Figure 4 Time Domain [41]

2.6.1   *GAUSSIAN MONOCYCLE*

Sending short pulses separated by relatively long time intervals yields a wide spectrum and a low duty cycle. Duty cycle is defined as the ratio of pulse width to time between pulses. Different pulse shapes are available but a commonly used waveform is the Gaussian pulse. In the time domain, the Gaussian monocycle is mathematically similar to the first derivative of the Gaussian function. It has the form:

$$V(t) = A\frac{t}{\tau}e^{-\left(\frac{t}{\tau}\right)^2} \qquad (5)$$

where

$V(t)$ =   Time domain Gaussian pulse

A   =   Arbitrary amplitude

τ =   Monocycle duration

t   =   Time

In the frequency domain, a Gaussian monocycle's spectrum is of the form:

$$V(f) = -jf\tau^2 e^{-(f\tau)^2} \qquad (6)$$

where

$V(f) =$ =   Gaussian pulse frequency domain response.

The center frequency is then proportional to the inverse of the pulse duration, i.e.:

$$fc \propto 1\;{1\!/\!\tau} \qquad (7)$$

The most basic element of Time Domain's TM-UWB radio technology is based on implementation of a Gaussian monocycle. Figure 5 shows an idealized monocycle in both the time and frequency domains [8].

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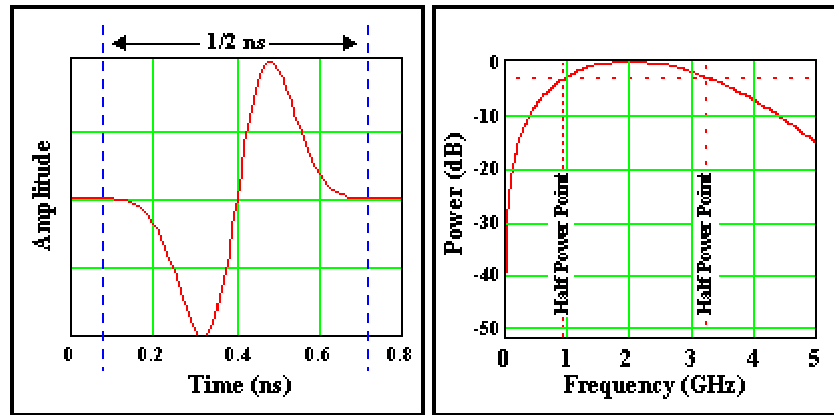
Figure 5 Gaussian Monocycle in Time and Freq. Domain [8]

The center frequency of a monocycle is the reciprocal of the monocycle's duration and the bandwidth is 116% of the monocycle's center frequency. Thus, for the 0.5 nsec monocycle shown in Figure 5, the center frequency is 2 GHz and the half power bandwidth is approximately 2 GHz.

TM-UWB technology places individual pulses at very precise times but with varying intervals. The pulses spread RF energy across an ultra-wideband spectrum. The TM-UWB architecture is characterized by:

1. Ultra-short duration pulses, which yield ultra-wide bandwidth signals

2. Extremely low power spectral densities

3. Center frequencies typically between 650 MHz and 5 GHz, with potential to go higher as technology advances

4. Multi-mile ranges with sub-milliWatt average power levels (even with low gain antennas)

5. Excellent immunity to interference from other radio systems.

In addition, Time Domain Inc. indicates the TM-UWB is expected to enjoy the following benefits:

1. Exceptional multipath immunity

2. Relatively simple and likely less costly to build than spread spectrum radios

3. Expected to consume substantially less power than existing conventional radios

4. Could be implemented as a simple integrated circuit chipset with very few off-chip parts

5. Capable of high bandwidth, multi-channel performance.

Because of these characteristics, UWB technology is being offered as a new technology for a wide variety of applications, including in-building communications systems, high-speed local area networks, home networks, cordless phones, security sensors, RF tags, and local high-precision positioning systems.

2.6.2 TECHNOLOGY BASICS

TM-UWB transmitters emit ultra-short "Gaussian" monocycles with tightly controlled pulse-to-pulse intervals. Time Domain has been working with monocycle pulse widths of between 0.20 and 1.50 nanoseconds and pulse-to-pulse intervals of between 25 and 1000 nanoseconds [37]. These short monocycles are inherently ultra-wideband. The systems typically use pulse position modulation (PPM). The pulse-to-pulse interval is varied on a pulse-by-pulse basis in accordance with two components: an information signal and a channel code. The TM-UWB receiver directly converts the received RF signal into a baseband digital or analog output signal. A receiver front end coherently converts the electromagnetic pulse train to a baseband signal in one stage. There is no intermediate frequency stage, greatly reducing system complexity.

A single bit of information generally modulates several multiple monocycles. The receiver coherently sums the proper number of pulses to recover the transmitted information.

2.6.3   A MONOCYCLE SEQUENCE

Time modulation systems use long sequences of monocycles for communications, not single monocycles. Data modulation and channelization are accomplished by varying the pulse-to-pulse time intervals. When transmitting such sequences, care must be taken to ensure the spectral quality integrity of the transmissions remains intact.

Figure 6 contains an illustration of a Gaussian monocycle sequence, or "pulse train." In the frequency domain, this highly regular monocycle pulse train produces energy spikes ("comb lines") at regular intervals [37]; thus, the already low power is spread among the comb lines. This monocycle pulse train carries no information and, because of the regularity of the energy spikes, may interfere with conventional radio systems at very short ranges. This would be undesirable.
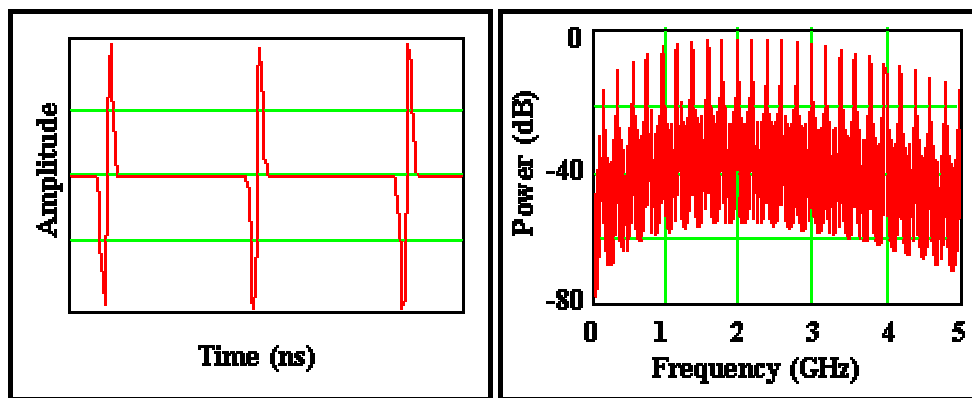

Figure 6 A Monocycle Pulse Train In The Time And Freq. Domain [8]

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By varying the pulse-to-pulse time intervals, the comb lines can be eliminated. This technique accomplishes data modulation and channelization as explained in the next sections.

2.6.4   MODULATION

To transmit information, additional processing is needed to modulate the monocycle pulse train.   Different companies implementing TM-UWB have taken different approaches for the modulation technique.   Frequency and phase modulation is unsuitable for this type of impulse communication.   Two possible choices are Pulse Position Modulation (PPM) and On Off Keying (OOK) [42-46].

In PPM, the information is coded as the relative position of pulses. Time Domain one of the UWB manufacturing companies, uses this modulation type in its proposed solutions [7].

TM-UWB systems use PPM since this technique allows the use of an optimal receiving matched filter technique. The receivers use a cross-correlator that gives the homodyne receiver the ability to find the signal well below the ambient noise level.

As illustrated in Figure 7, PPM varies the precise timing of a monocycle transmission about the nominal position. For example, in a 10 million pulses per second (Mpps) system, monocycles would be transmitted nominally every 100 nanoseconds (represented in Figure 7 as the time period PRI_{avg}). In such a system, a "0" digital bit might be represented by transmitting the pulse 100 picoseconds early and a "1" digital bit by transmitting the pulse 100 picoseconds late [37]. As shown in the right hand graph in Figure 7, PPM distributes the RF energy more uniformly across the band.   The

modulation smoothes the signal spectrum, thus making the system less detectable. However, because information modulation moves the pulses only a fractional part of a pulse width, this spectral smoothing impact is small.
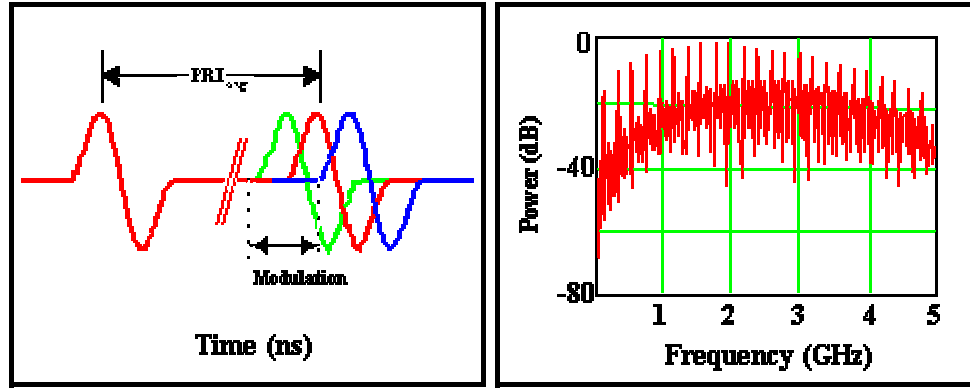
Figure 7 Pulse Position Modulation [8]

By contrast to PPM, OOK is commonly used in fiber optics but can also be used with the TM-UWB concept. The UWB manufacturing company MSSI uses this type of modulation in its applications. A pulse represents a one bit and a zero bit is represented with absence of a pulse in the expected position [6].

2.6.5   CODING FOR CHANNELIZATION

At this point, any modulated pulse train looks like any other pulse train; it is not channelized. However, by shifting each monocycle's actual transmission time over a large time frame in accordance with a code, a pulse train can be channelized. As illustrated in Figure 8, a relatively large time offset (many nanoseconds) is applied to each impulse. "Pseudo-random noise" codes (PN codes) are used for this purpose. In a multiple access system, each user would have a unique PN code sequence. Only a receiver operating with the same PN code sequence can decode the transmission.
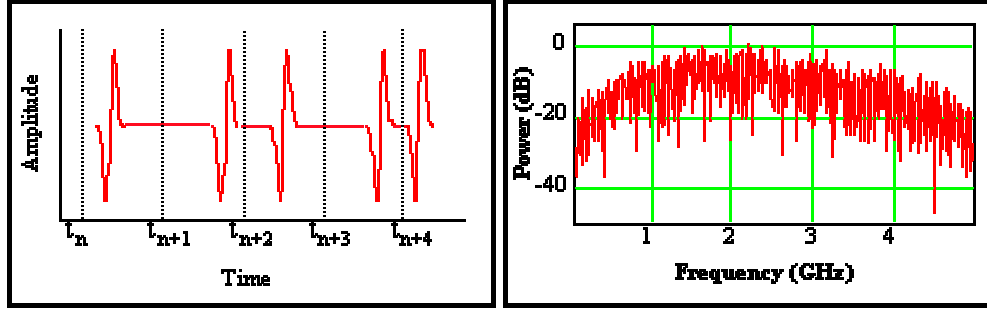
Figure 8 Impact of Pseudo-Random Time Modulation [37]

In the frequency domain, this pseudo-random time modulation makes a TM-UWB signal appear indistinguishable from white noise. In the time domain, each user could have a unique pseudo-random time-hopping code and the system could then have a virtually unlimited number of channel codes.

Without knowledge of the unique time-hopping code, the signal is virtually undetectable, even within very close proximity of the transmitter. This makes the signal inherently difficult to detect or intercept other than by the matched correlation receiver. As a reference point, TM-UWB systems typically have very low duty cycles with repetition frequencies between 1 and 40 Mpps. Figure 8 exaggerate the typical duty cycle found in Time Domain's prototypes. In typical implementations, the actual duty cycle is less than 1%.

2.6.6 RECEIVING MONOCYCLE TRANSMISSIONS

Having generated a signal with minimal spectral features, it is also necessary to have an optimal receiving system. The optimal receive technique, and the technique used in TM-UWB, is a time-gated correlation receiver. A correlator multiplies the received RF signal with a "template" waveform and then integrates the output of that process to

yield a single DC voltage. This multiply-and-integrate process occurs over the duration of the pulse and is performed in less than a nanosecond.

With the proper template waveform, the output of the correlator is a measure of the relative time positions of the received monocycle and the template. Figure 9 shows the output of the correlator that corresponds to different time offsets between the template and the received waveform. As shown, the correlator is an optimal early/late detector. When the received pulse is ¼ of a pulse early, the output of the correlator is a (+1); when it is ¼ of a pulse late, the output is (-1); and when the received pulse arrives centered in the correlation window, the output is zero. It is critical to note that the mean value of the correlator is zero. Thus, for in-band noise signals received by a TM-UWB radio, the correlator's output value has an average value of zero. Moreover, the standard deviation (RMS) of the correlator output is related to the power of those in-band noise signals.

When a monocycle is buried in the noise of other signals, it is impossible to detect the reception of a single TM-UWB pulse. However, by adding together numerous correlator samples, it becomes possible to receive transmitted signals. This process is called "pulse integration." Through pulse integration TM-UWB receivers can acquire, track and demodulate TM-UWB transmissions that are significantly below the noise floor [37]. The measure of a TM-UWB receiver's performance in the face of in-band noise signals is processing gain.
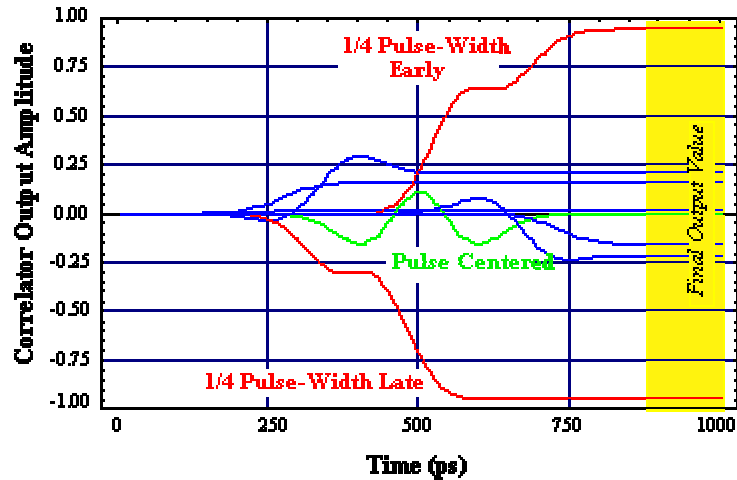
Figure 9 Correlator Output [37]

2.6.7 *PROCESSING GAIN AND INTERFERENCE RESISTANCE*

The combination of pseudo-random coding, random time modulation and a correlating receiver make time-modulated radios and radars highly resistant to interference. This is critical as all other signals within the band occupied by a time-modulated signal act as jammers to the time-modulated radio. Since there are no unallocated multiple GigaHertz bands available for time-modulated systems, time modulated radios will have other signals within their operating band.

Processing gain provides a measure of a radio's resistance to jamming. Processing gain is defined as the ratio of the signal's RF bandwidth to the information bandwidth. Time-modulated radios have large processing gain. For example, a CDMA spread spectrum system with an 8-kHz information bandwidth and a 1.25-MHz channel bandwidth has a processing gain of 156 (22 dB). A TM-UWB system transmitting the same 8-kHz information bandwidth with a 2-GHz channel bandwidth has a processing gain of 250,000 or 54 dB. Alternatively, the process gain for a TM-UWB signal may be

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calculated from: the duty cycle of the transmission, e.g., a 1% duty cycle yields a process gain of 20 dB. The effect of pulse integration, e.g., integrating energy over 100 pulses to determine one digital bit yields a process gain of 20 dB. The total process gain is then the sum of these two components, e.g., 40 dB. For example, a 2-GHz / 10-Mpps link transmitting 8 kbps would have a process gain of 54 dB, because it has a 0.5-ns pulse width with a 100-ns pulse repetition interval = 0.5% duty cycle (23 dB) and 10 Mpps / 8,000 bps = 1250 pulses per bit (another 31 dB).

2.6.8   BLOCK DIAGRAM OF TM-UWB TRANSCEIVER

Figure 10 is a high-level block diagram of a TM-UWB transceiver [37]. As shown, the transmitter does not contain a power amplifier. Instead a pulse generator at the requisite power generates the transmitted pulse. A critical part of the pulse generation circuit is the antenna, which acts as a filter [37]. The receiver resembles the transmitter, except that the pulse generator feeds the multiplier within the correlator. Also, baseband signal processing must extract the modulation and control signal acquisition and tracking.
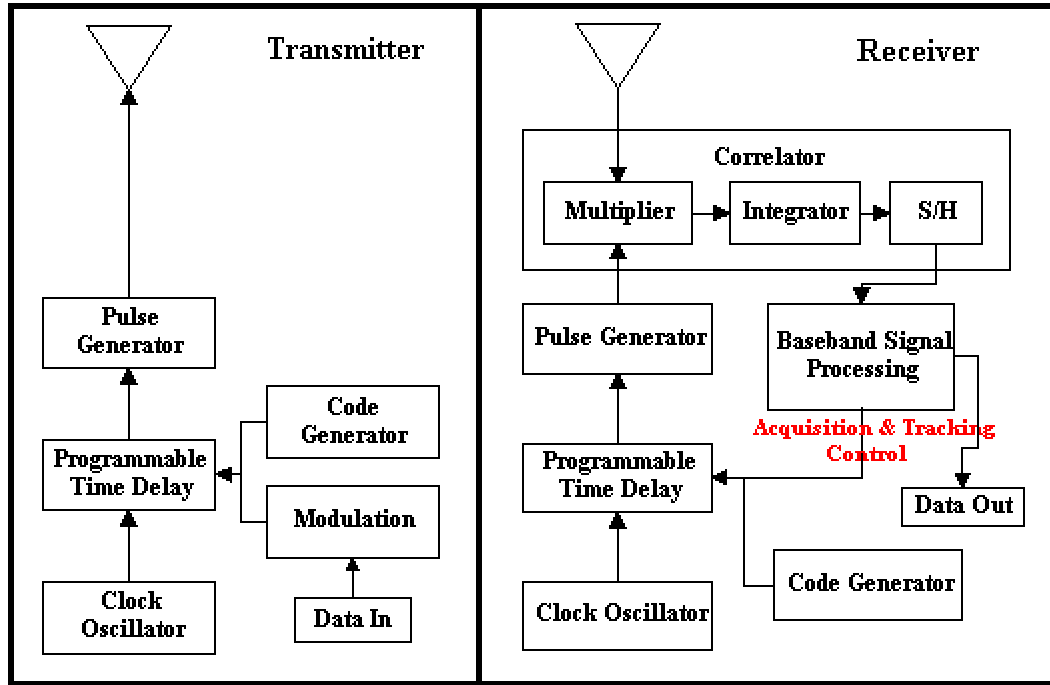
Figure 10 TM-UWB Transceiver Block Diagram [37]

2.6.9 *MULTIPATH AND PROPAGATION*

Multipath fading is an inevitable result when continuous sine waves are transmitted inside buildings. The transmitted signals will reflect and suffer destructive cancellation. This fading can only be mitigated by increasing the transmit power by 20 dB and/or employing more elaborate architectures and signal processing.

A time-modulated system incorporating a rake receiver does not experience this effect. As shown in Figure 11, a monocycle travels from a transmitter to a receiver along two paths. Since the paths are of two different lengths, the second pulse will arrive after the first pulse. A receiver could lock on either pulse and receive a strong signal. Indeed, if two correlators were used it would be possible to lock on to both signals and coherently add the energy thereby increasing the received signal-to-noise ratio.
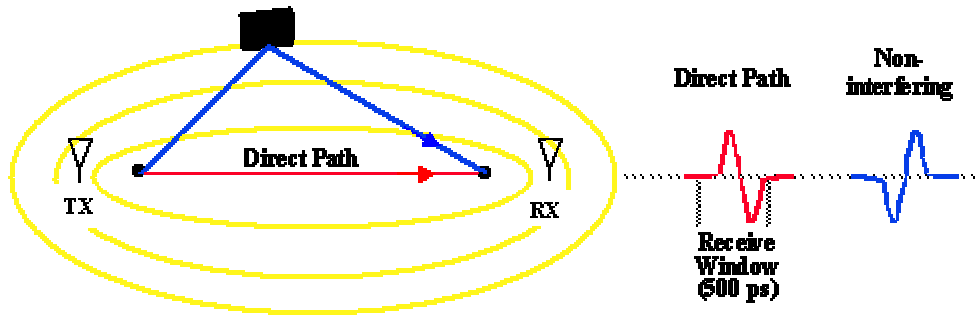
Figure 11 Multipath in a TM-UWB System [37]

When a train of pulses is transmitted, it is possible that a given pulse may be interfered with by a late-arriving reflection from a previous pulse. However, because each individual pulse is subject to pseudo-random time modulation and bit energy is spread over more than one pulse, these interfering pulses are decorrelated and can, for the most part, be ignored.

2.6.10 DIFFERENCE BETWEEN UWB AND DSSS

The spread bandwidth for a UWB waveform is generated directly, i.e., without individual spreading modulation by a separate spreading sequence such as a PN code or hopping (*chipping*) pattern, which is the case for conventional spread spectrum waveforms (whether direct sequence DSSS or frequency hopping FHSS). Thus, UWB is essentially a time-domain concept in which an extremely short RF pulse directly generates a very wide instantaneous bandwidth signal This is due to the time-scaling properties of the Fourier transform relationship between time and frequency. Recall this relationship from Equation 4.

In addition, DSSS or FHSS waveforms are *constant envelope* in nature [35]. That is, their instantaneous amplitude does not change with time. For a DSSS waveform,

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individual transmission bits are further subdivided into biphase-modulated chipping intervals; while for FHSS, individual transmission bits are further subdivided into distinct frequency changes. As a consequence, spread spectrum waveforms typically have unity (100%) duty cycle i.e., peak and average power levels are equal. With UWB, on the other hand, pulse durations are extremely short relative to pulse arrival times. Thus, waveform duty cycles are typically small fractions of a percent, and peak-to-average ratios can be quite large.

From a communications perspective, the performances of both types of systems (whether spread spectrum or UWB) are determined by the effective energy per bit to noise spectral density ratio E_b/N_0. As shown in Equation 8

$$N_0 = kT_eB \tag{8}$$

where

$$k \quad = \quad \text{Boltzmann's constant}$$

$$T_e \quad = \quad \text{The effective system noise temperature (Kelvin)}$$

$$B \quad = \quad \text{The instantaneous bandwidth (Hertz}$$

It is apparent that the wider the bandwidth, the more energy is needed for communications. For a UWB system, $E_b = PT$ with peak pulse power P and effective pulse duration T. Thus, the shorter the pulse is, the higher the necessary peak power for a given bit error rate (BER) performance (identical issues exist for radar performance as well). For a spread spectrum waveform, E_b is also given by PT; with T representing the *bit* duration (i.e., NT_c where N is the processing gain and T_c is the chip duration).

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However, there are some other differences between UWB and spread spectrum. These include:

1.   Lower implementation complexity and cost for extremely high bandwidths -- and, thus, high data throughputs

2.   Independence of BER performance with change in data rates -- for a constant envelope waveform, a doubling of the data rate requires a doubling of the peak and average power

3.   Potential for mobile multipath immunity and dual use (i.e., radar & communications) applications

The practical limit on the achievable LPI/LPD for a UWB communications system was determined by the minimum achievable pulse width given a peak power constraint at the transmitter while the practical limit for DSSS was determined by the maximum achievable processing gain given a realizable level of a receiver complexity [35].

III.   EQUIPMENT CONFIGURATION AND TEST SET-UP

3.1   CHAPTER OVERVIEW

This chapter outlines the proper setup for taking measurements with the PADs used during this research. Chapter 2 explained that Ultra wideband signals are often defined such that their 3 dB bandwidth is at least 25% of the center frequency. This characteristic means that such signals can normally coexist with narrowband signals with none of these systems suffering intolerable interference problems. Exceptionally wide bandwidths at the lowest possible frequencies will result in very fine time resolution for accurate ranging, imaging, and multipath fading mitigation.

This chapter also describes an approach to develop accurate, repeatable, and practical methods for characterizing the very narrow pulses (and pulse trains) of UWB systems. The purpose of this characterization is to provide the information necessary to estimate or measure the potential for existing (narrowband, channelized, band-limited, and wideband) radio communications or sensing systems to interfere with the TM-UWB system.

The first step defines operational contexts and user scenarios for wireless applications requiring combined data communication and location tracking. For selected scenarios, the requirements are determined in terms of communication needs and location information (e.g., distance, direction, position accuracy). The second step defines and evaluates the PADs ability to accomplish simultaneous data communication and location tracking, which is required for personnel location and physiological monitoring.

3.2   *SUSCEPTIBILITY OF UWB TO IN-BAND INTERFERENCE*

The UWB receiver design is the strongest factor in determining its vulnerability to in band interference. In baseband architectures the equivalent receiver front end is typically left wide open, with RF filtering performed only by the receiver antenna itself. The antenna itself provides little or no filtering of "out-of-band" signals and noise. For this reason, some of these systems incorporate additional lowpass or bandpass filtering prior to the receiver amplifier/detector stages. Unfortunately, while helping to remove interference, this additional receiver filtering also removes desired signal energy [6].

Correlating receivers, in which the received waveform is essentially template-matched with a local replica of the transmitted waveform, also have little immunity to broadband noise or impulsive interference. This is due to the fact that any impulse or white Gaussian noise excitation of the wideband receiver front end produces a received waveform having characteristics very similar to those of the transmitted waveform. And, of course, a strong in-band continuous wave (CW) interferer can similarly create destructive interference with such simple receiver architectures by simply overloading the detector.

Time-gated correlating receivers, in which the correlation operation is gated to the pulse duration and synchronized to the incoming bit stream, have been quite effective in reducing the effects of in-band interference in UWB receiver architectures [6].

3.3 PAD RECEIVER LOSSES

Figure 12 shows a simplified block diagram of the PAD receiver. "G" signifies gains, L refers to losses, and NF refers to noise figure. Given values for the gains, losses, and noise figures, one is able to calculate the system losses of the receiver.
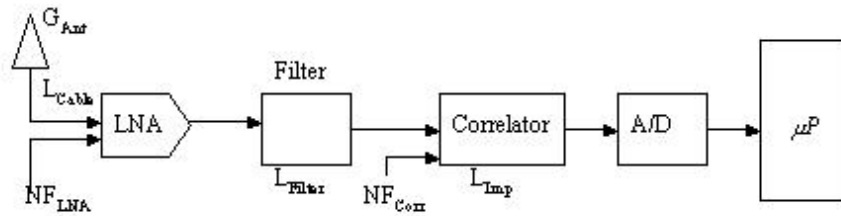
Figure 12 Receiver Block Diagram

When calculating the total noise at higher frequencies the Friis transmission formula is very important. The formula describes the total noise-factor of an antenna-system [47].

$$NF_{Total} = NF1+(NF2-1)/G1+(NF3-1)/G1*G2+... \qquad (9)$$

Typical PAD characteristics in terms of the gains, losses, and noise figures for the architecture shown in Figure 12 are [48]:

G_{Ant} = 0dBi

G_{LNA} = 30.0 dB

NF_{LNA} = 2.1 dB

L_{Imp} = 6.0 dB

$$L_{Filter} \quad = \quad 8.0 \text{ dB}$$

$$L_{Cable} \quad = \quad 2.0 \text{ dB}$$

$$NF_{Corr} \quad = \quad 19.0 \text{ dB}$$

Combining the filter loss and the correlator noise figure gives:

$$NF_{Filter} = 8+19 = 27 \text{ dB}$$

When the Friis Formula is applied:

$$NF_{Total} = 10^{\frac{2.1}{10}} + \frac{10^{\frac{27}{10}} - 1}{10^{\frac{30}{10}}} = \textit{2.122 which is 3.3 dB.}$$

The total PAD system losses are now the combined values of total noise figure and implementation losses.

$$\text{System Losses} = NF_{Total} + L_{Imp} + L_{Cable} = 3.6 + 2 + 6 = 11.2 \text{ dB.}$$

3.4 EQUIPMENT CONFIGURATION AND TEST SET-UP

The TM-UWB PAD is the primary hardware used in this research to test the UWB technology performance for different applications in different environments. These PADs have been developed by Time Domain Corporation based upon the Time Modulated Ultra Wideband (TM-UWB). Depending on your setup needs, the PAD can be configured as a transmitter, a dual-channel receiver, or a transceiver through its various cable configurations. It can be configured to receive raw data by connecting the receiving antenna directly to the correlator or refine the data by running the receiver through the low-noise amplifier and filter before sending it to the correlator. The PAD is software controllable via its Ethernet™ port. This port can be configured for either LAN

usage or for a direct PC connection. Both transceivers were connected to laptops. The PADs communicate with each other using the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol. Detailed information about the TCP/IP is presented in 3.4.2.

The Xpod® evaluation kit was used to produce physiological data. Information about the Xpod® evaluation kit is covered in 3.4.1.4.

The Hewlett Packard (HP) HP8672A (2 - 18 GHz) and HP 8350B (0.1 - 2.4 GHz) signal generators were used to generate interference signals as specified for test scenarios. An external HP variable attenuator was used to vary signal level output. An Hp 8563A spectrum analyzer was used to measure interference characteristics.

3.4.1 HARDWARE SETUP

The Scanning Receiver, Wireless Local Area Network (WLAN), and Precise Location Tracking (PLT) have slightly different configurations and setup techniques.

3.4.1.1 SCANNING RECEIVER SET-UP

The PAD Scanning Receiver is a software application used in conjunction with the PAD platform to evaluate Time Domain's PulsON technology. It requires two PAD units - one designated as the transmitter and the other as the receiver. The transmitting PAD sends a data stream composed of an ANSI standard bit error rate test pattern at a user-specified bit rate. The receiving PAD captures the impulse response waveform.

For Scanning Receiver applications, each PAD should be configured as a separate transmitter and receiver. The transmitter PAD set-up and configuration is done as shown in Figure 13.
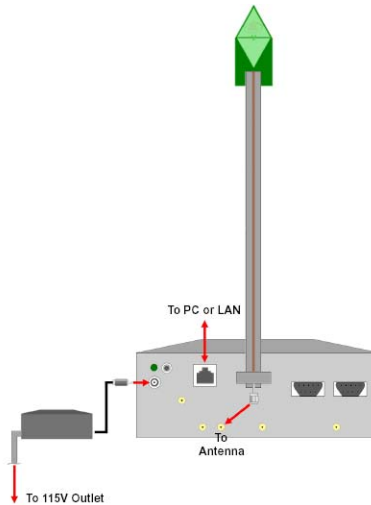
Figure 13 Transmitter Configuration

Before applying power to the PAD, one must ensure the connector nut is firmly tightened over each connection to avoid accidental disconnection. Since the connector center pins on the SMA cables are extremely fragile, over tightening must be avoided. If resistance is met while connecting a cable to a port, either during insertion or when tightening the connector nut, this attempt must be aborted and tried again [37].

The receiving PAD set-up configuration is given Figure 14.
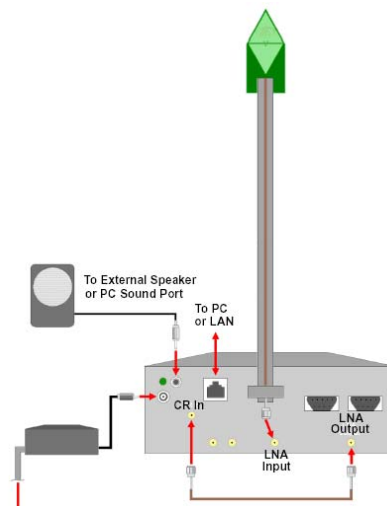
Figure 14 Receiver Configuration

One should be careful about the exact considerations mentioned in 3.4.1.1

3.4.1.2 WLAN SET-UP

PAD capabilities include unicast video, multicast video (as done with a Windows 2000 server), audiovisual conferencing (as with Microsoft NetMeeting), web browsing, Internet and LAN games, ftp, telnet, and file sharing. The WLAN demonstration uses Microsoft® NetMeeting® to demonstrate the point-to-point or multipoint-to-multipoint connectivity. You can demonstrate a videophone, chat feature, whiteboard, or even file transfer from one unit to another. The Radio Controller program must be running on a PC using Windows NT or Windows 2000. There must be at least one PC connected to each PAD through Ethernet wires, in order to initialize it. Once a PAD has been initialized and is participating in the WLAN, it is not necessary for the PC to remain connected to the PAD. For the WLAN application, PADs should be configured as transceivers. The PAD Communications Demo uses a wireless network hub, similar to a free space hub with the radio links serving as information connections lines. The PAD connections should be made according to Figure 15.
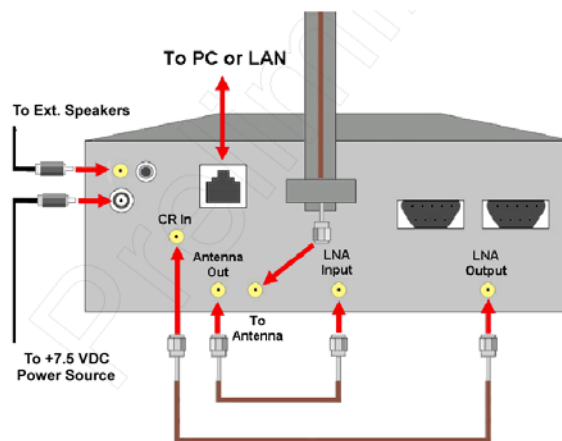
Figure 15 Transceiver Configuration

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Sifter capability gives WLAN capability to communicate to/from a specific PAD. When the sifter is enabled in a PAD, the PAD only transmits packets destined for nodes local to other PADs, and it transmits broadcast packets. Packets whose destination MAC address is not the address of a node on another PAD are not transmitted.

3.4.1.3 PRECISION LOCATING AND TRACKING SET-UP

When set-up is done as a PLT, its capabilities include, three-dimensional tracking and distance measuring, calculating angle-of-arrival, and detecting movement between PADs which is called security fence. Half-duplex ranging demonstrations require one PAD as a responder unit and the other one as a requestor unit. Hardware configuration for both PADs is identical. The responder PAD need only be powered on to be ready for the demonstration. A PC does not have to be attached to the PAD for operation.

The PAD connections should be made according to Figure 16 (identical to WLAN connection).
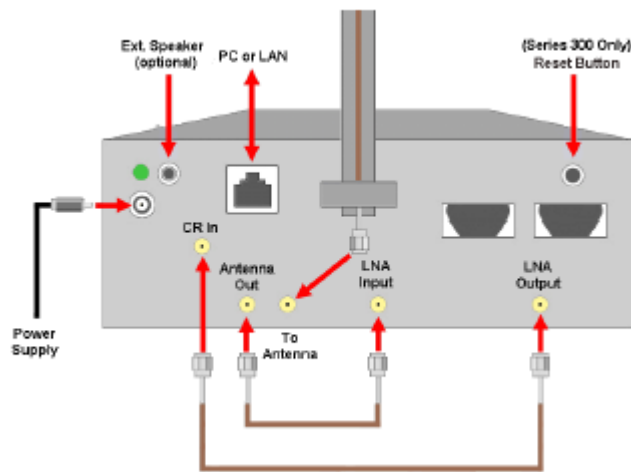
Figure 16 Single Antenna Transceiver

3.4.1.4 PHYSILOGICAL DATA

The Xpod® evaluation kit was utilized to generate the physiological data to evaluate the Pad's modulation performance via its bit stream. The evaluation kit includes:

1. Xpod®

2. 9 volt Battery

3. Evaluation Program Install Diskette

4. Sensor

5. Xpod® Serial Interface Computer Cable with Lemo Connector

Xpod® evaluation kit displays time, heart rate, SpO2 and perfusion information in real time. Additionally, this information can be saved as an ASCII code in a file.

3.4.1.5 TEST SET-UP

The following configuration was set up at AFIT in room 141.   The equipment

used in the research included two PADs, HP signal generators, an HP spectrum analyzer,

variable attenuator and microwave absorbing panels (MAP).

Figure 17 Test Configuration

3.4.1.6 TYPICAL SCENARIO

A typical scenario is a firefighter inside a burning building with a command and control center, police, and emergency medical personnel located around the building. Potential interfering sources around the fire scene include police, fire, and medical radio networks. The transponder-equipped firefighter inside the building, as well as similarly equipped personnel outside, send their position and physiological information in real-time to the command and control center and each other.

3.4.2 TCP/IP PROTOCOL
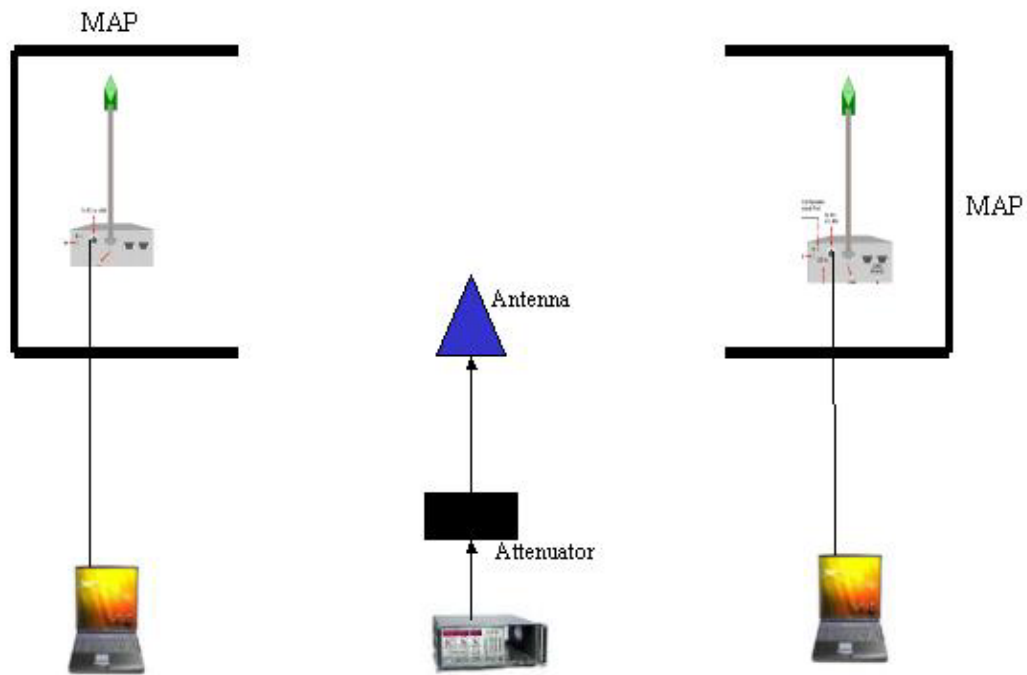
The PADs communicate with each other using the TCP/IP protocol. TCP and IP were developed by a Department of Defense (DOD) research project to connect a number different networks designed by different vendors [49]. It was initially successful because it delivered a few basic services that everyone needs (file transfer, electronic mail, remote logon) across a very large number of client and server systems. The IP component provides routing from the department to the enterprise network, then to regional networks, and finally to the global Internet. On the battlefield a communications network will sustain damage, so the DOD designed TCP/IP to be robust and automatically recover from any node or phone line failure. This design allows the construction of very large networks with less central management. However, because of the automatic recovery, network problems can go undiagnosed and uncorrected for long periods of time. As with all other communications protocol, TCP/IP is composed of layers [48,49] including:

1. IP is responsible for moving packet of data from node to node. IP forwards each packet based on a four-byte destination address (the IP number). IP is the central,

unifying protocol in the TCP/IP suite. It provides the basic delivery mechanism for packets of data sent between all systems on an Internet, regardless of whether the systems are in the same room or on opposite sides of the world.

2. TCP is responsible for verifying the correct delivery of data from client to server. Data can be lost in the intermediate network. TCP adds support to detect errors or lost data and to trigger retransmission until the data is correctly and completely received. TCP provides a reliable byte-stream transfer service between two endpoints on an Internet. TCP depends on IP to move packets around the network on its behalf. IP is inherently unreliable, so TCP protects against data loss, data corruption, and packet reordering and data duplication by adding checksums and sequence numbers to transmitted data and, on the receiving side, sending back packets that acknowledge the receipt of data.

3.5   INTERFERENCE SCENARIOS

As specified in 3.4.1.6, the scenario involves a typical fire department response to a structure fire. The primary interference sources and their operational frequency bands of are listed in Table 2.   The interference sources were simulated using HP signal generators.

Table 2 Potential Interference Sources

Interference Source	Frequency Range
CH. 2 SECONDARY FIRE GROUND	458.475
HANDHELD (MOTOROLA SPIRIT PRO+ 2 WATT UHF)	469.2625
POLICE (INDIANA LAW ENF. NETWORK – TACT 2)	155.4750
POLICE (INDIANA STATE POLICE)	042.3200
POLICE (TIPPECANOE CTY SHERIFF)	859.7375
FIREFIGHTING EMERGENCY AIR TACTICS	118.9250
EMERGENCY	121.5000
UNICOM (HELICOPTERS)	123.0250
SEARCH & RESCUE	123.1000
GROUND CONTROL (AIR-TO-GROUND)	121.6000

3.5.1   RADIATED MEASUREMENTS

Different test setups were implemented for the radiated measurements. All the test setups were performed in the microwave lab, room 141 AFIT's semi-anechoic chamber.   The PADs-under-test radiated, using its manufacturer-supplied omni directional antenna into the chamber. The interference source's antenna was a ridged horn antenna; see for Figure 17 for the test set-up. The measurement frequency range using this antenna was 200 MHz to 1800 MHz. and 2 GHz to 5 GHz. Ten attenuation stages were needed in this configuration to provide enough or desired SNR values. By

using the attenuator the strength of the interference signal can be adjusted thus enabling us to get and observe the received signal's SNR value we want.

3.6 CHAPTER SUMMARY

This chapter provided an overview of the equipment configuration used for the evaluation of the PADs. Depending on your setup needs, the PAD can be configured as a transmitter, a dual-channel receiver, or a transceiver through its cable configuration. The PAD Scanning Receiver is a software application used in conjunction with the PAD platform to evaluate Time Domain's PulsON technology. It requires two PAD units; one designated as the transmitter and the other as the receiver. WLAN is the other software application used to evaluate the TM-UWB's modulation/demodulation performance. The research focuses on the performances of the Scanning Receiver and WLAN applications under different interference environments. The results are discussed in Chapter 4.

IV.   RESULTS AND ANALYSIS

4.1   CHAPTER OVERVIEW

This chapter presents and examines the radiated measurement results for the PADS. The Scanning Receiver, WLAN and PLT applications are analyzed separately in similar interference environments. The indoor and outdoor performance of the PADS and the their comparison with narrow band radios are also evaluated.

4.2   PAD INDOOR AND OUTDOOR RANGE vs. DATA RATE
PERFORMANCE

This section describes a free space propagation model that optionally includes attenuation due to walls. The received SNR of a UWB radio system can be written entirely in terms of transmitter effective radiated power P_T (Watts) the system data bandwidth B_D (Hertz) the UWB transmission center frequency f (Hertz) transmission distance d (meters) and system loss budget L_{sys} [48,50]. The equation is shown below:

$$SNR = 10\log(P_T) - 10\log(B_D) - 10\log(kT) + P_L + L_{sys} \qquad (10)$$

where

$$
\begin{aligned}
k \quad &= \quad 1.38 \text{x} 10\text{-}23 \text{ J/K Boltzmann's constant} \\
T \quad &= \quad 290 \text{ K, the nominal noise temperature} \\
P_L \quad &= \quad \text{Free space path loss between the antennas}
\end{aligned}
$$

.

$$P_L = 20\log\left(\frac{c}{4\pi dfd}\right) - L_w(d-4)\psi \qquad (11)$$

where

c = Velocity of light. (m/sec)

L_w = In building losses which is in dB per meter beyond 4

meters

Ψ = 1 if d is greater than 4

Ψ = 0 if d is less than 4

Here, c is the velocity of light; in-building losses are modeled by a constant L_w dB per meter beyond 4 meters. The function Ψ here is 1 for $d > 4$ and zero otherwise. Previous research indicated that the average building losses are L_w=0.7 dB/m [51]. The system losses L_{sys} include receiver noise figure and implementation losses.

Figures 18 to 24 show the predicted data rate capability, up to the maximum PAD data rate of 10 Mbps, as a function of the UWB radio link distance for four UWB system scenarios operating at a center frequency of 1.9 GHz. Table 3 shows the scenarios.

Table 3 Scenario

Scenario	SNR (dB)	P_T (watts)	Antenna Gain (dBi)	Imp. Loss (dB)
1	10	50e-3	2.0	11.2
2	10	120e-6	2.0	6.0
3	20	2.5e-3	6.0	6.0
4	14	10e-3	1.0	11.0

Figure 18 shows the PAD range capability vs. data rate. The solid curve shows the indoor performance the green one shows the outdoor performance.
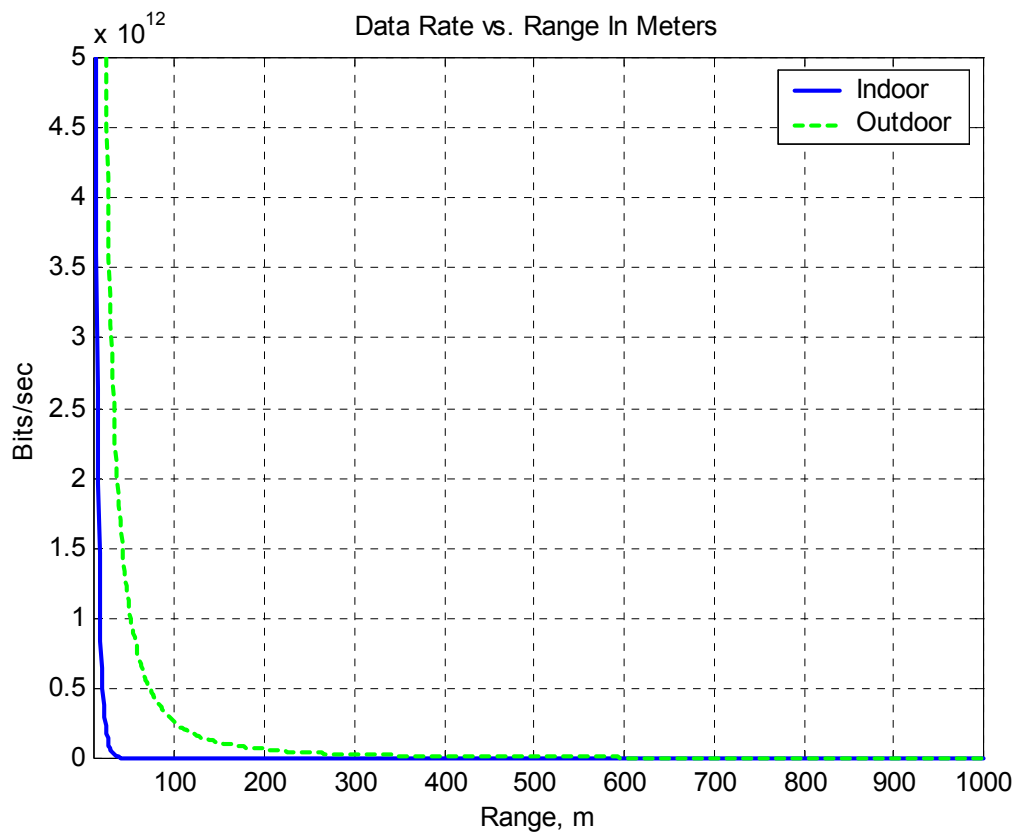
Figure 18 PAD Range Performance

Figure 19 shows the same scenario (indoor only) with a different scale. The maximum range for the PAD exceeds 100m indoors.

Figure 19 PAD Range Performance

The severe impact of the exponential losses due to the L_w term in Equation 11 is noticeably evident and is a major limiting factor for indoor propagation

Figure 20 shows the average in-building performance for $P_T = 120$ μ watts power using 2 dBi wide band dipoles in a system with 6 dB total system losses and providing 10 dB SNR.
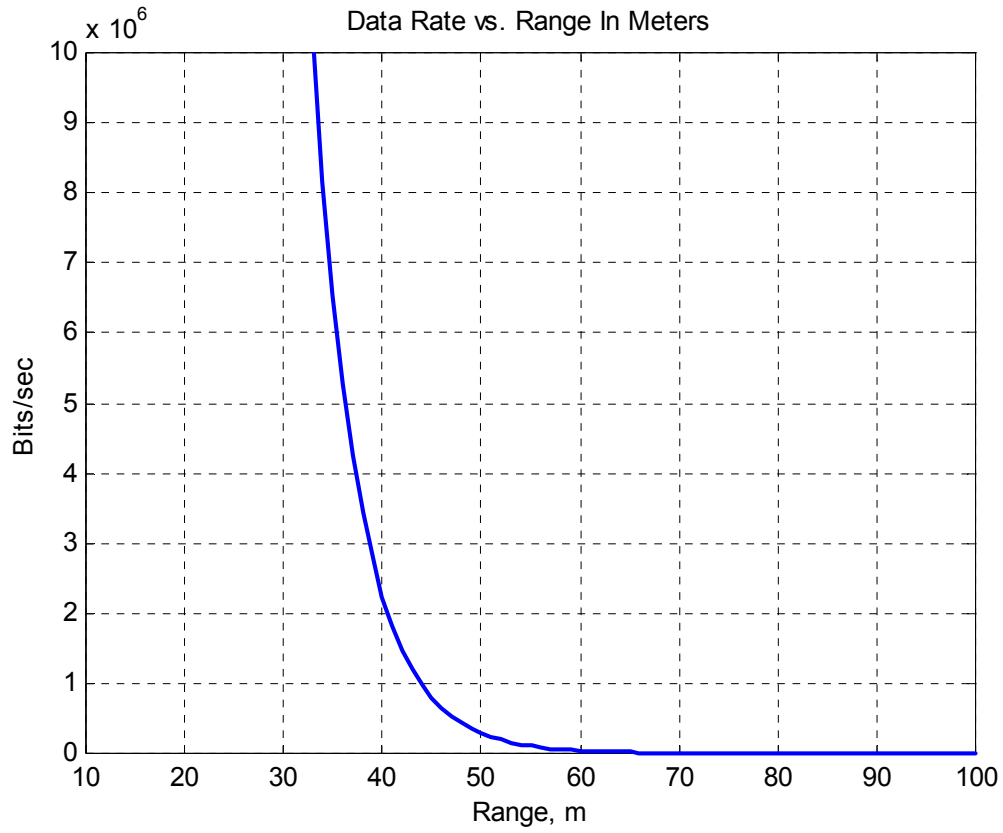
Figure 20 UWB System Range Performance

The only difference between Figure 20 and Figure 21 is that Figure 21 focuses on the lower data rate for the same scenario.
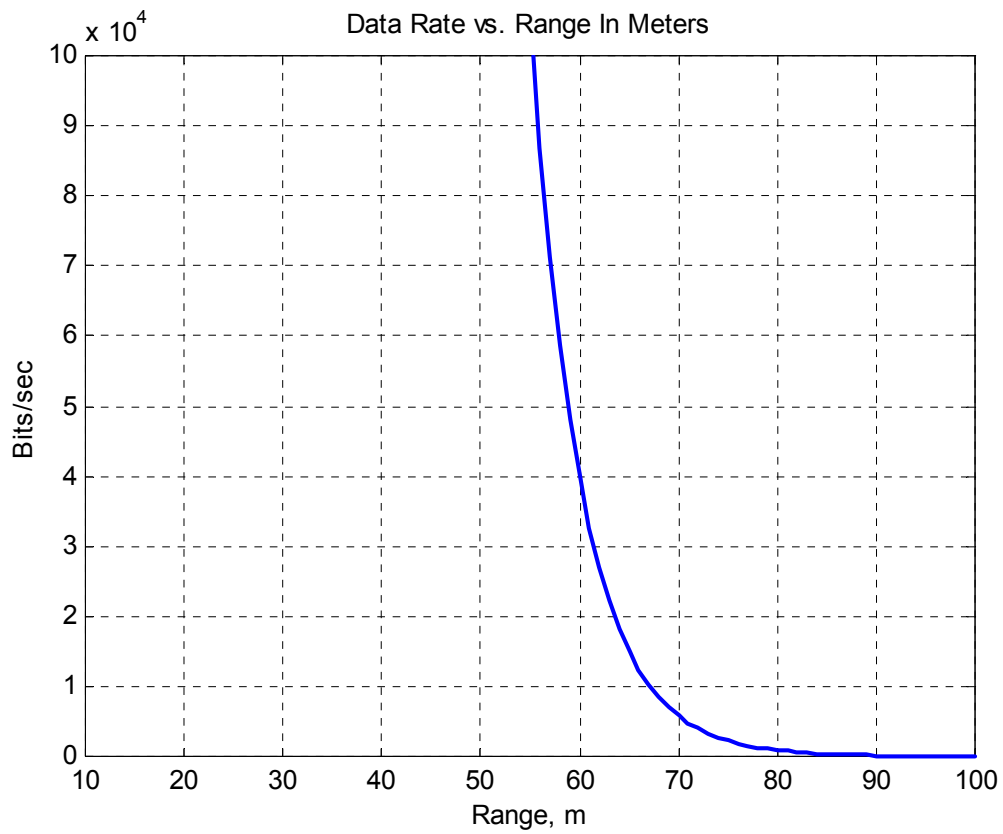
Figure 21 UWB System Range Performance

Figure 22 shows the same system with $P_T = 2.5$ milliWatt-transmitted power using a 6 dBi receive antenna without the in-building wall losses and providing a 20 dB SN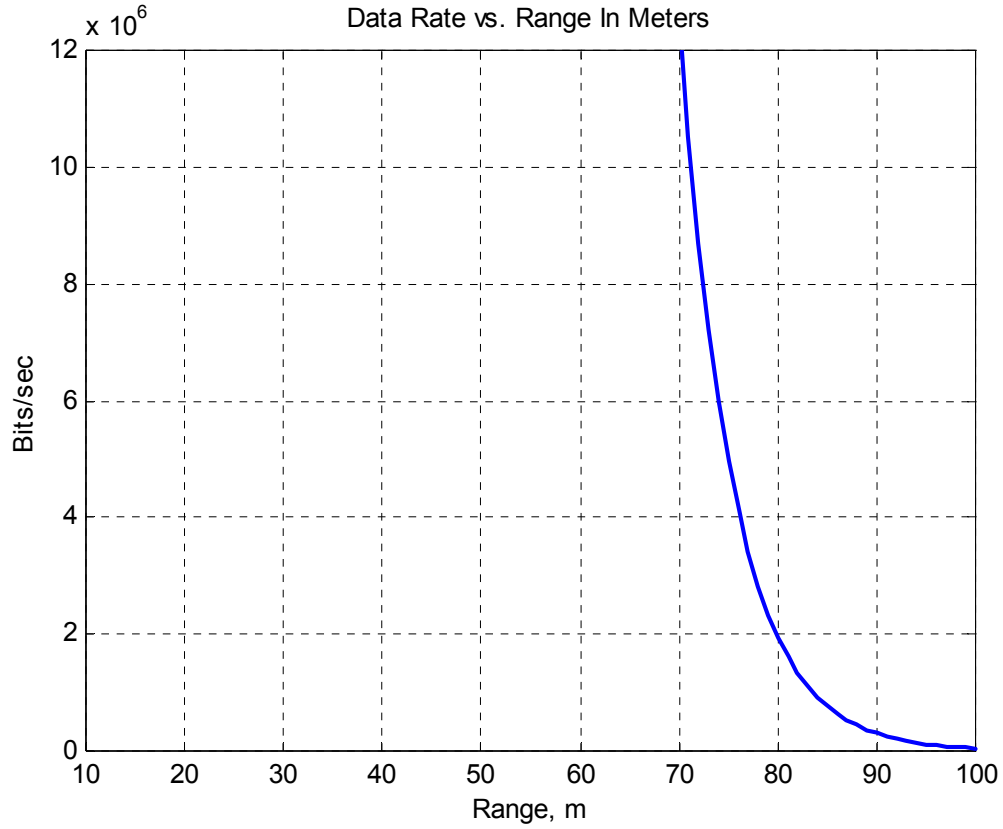R. Again the severe impact of the exponential losses due to the L_w term in Equation 11 is noticeably evident and is a major limiting factor for indoor propagation.
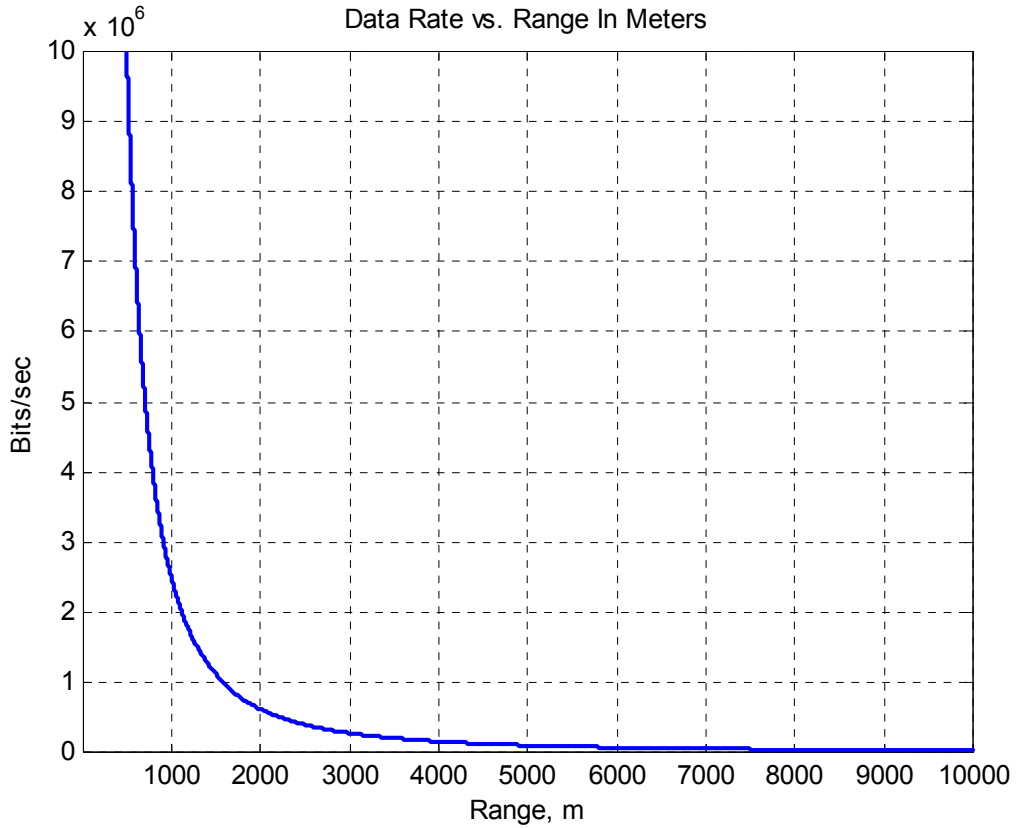
Figure 22 UWB System Range Performance

Again Figure 23 focuses on the lower part of the data rates.
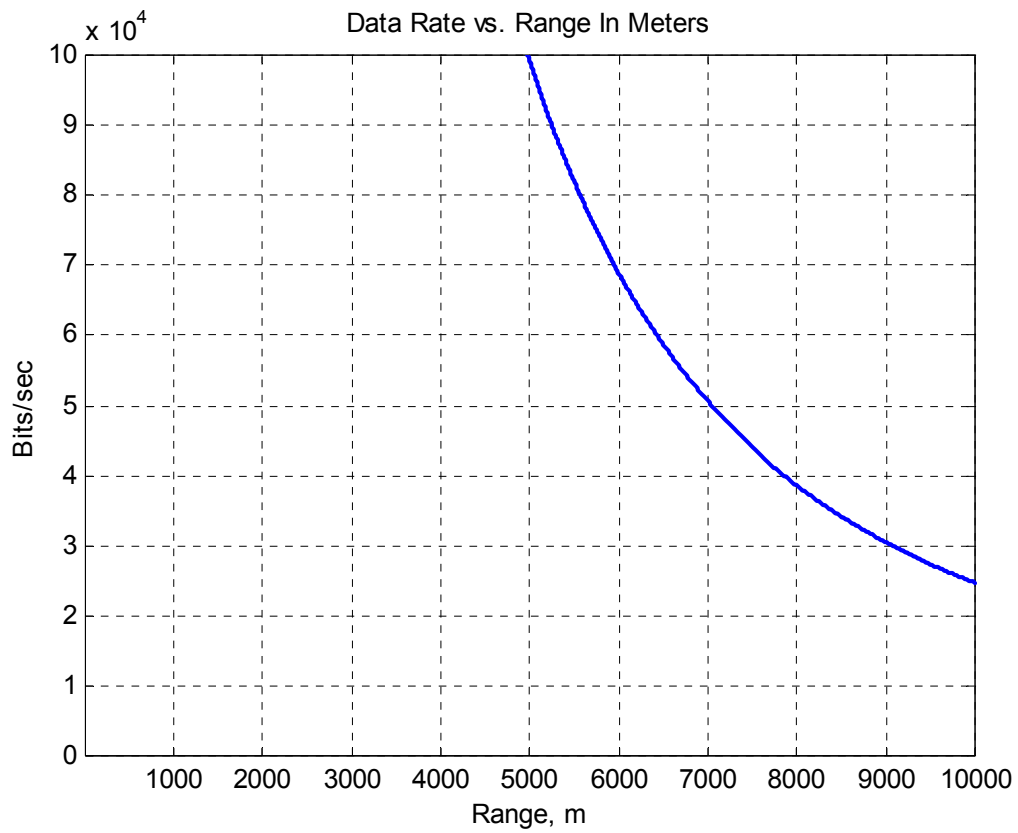
Figure 23 UWB System Range Performance

Figure 24 models an outdoor case operating at 10 milliWatt transmitted power, with 1 dBi receiver antenna, 11 dB implementation losses, and providing a 14 dB SNR
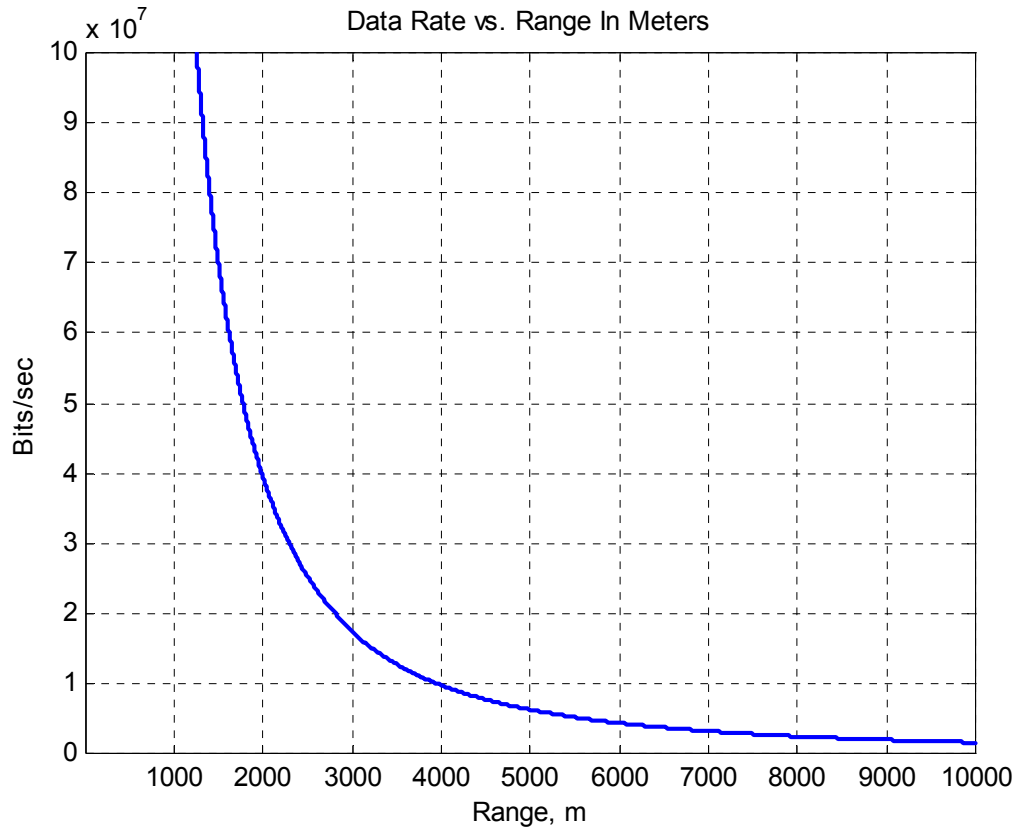
Figure 24 UWB System Range Performance

4.3   RESULTS OF RADIATED EXPERIMENTS FOR SCANNING RECEIVER APPLICATION

A major goal in this research was to figure out the BER vs. SNR performance for the Scanning Receiver application in an interference environment. One can easily check the SNR values and can lock/unlock the receiver via the Radio Controller software interface, which is displayed on receiver's laptop screen, shown in Figure 25
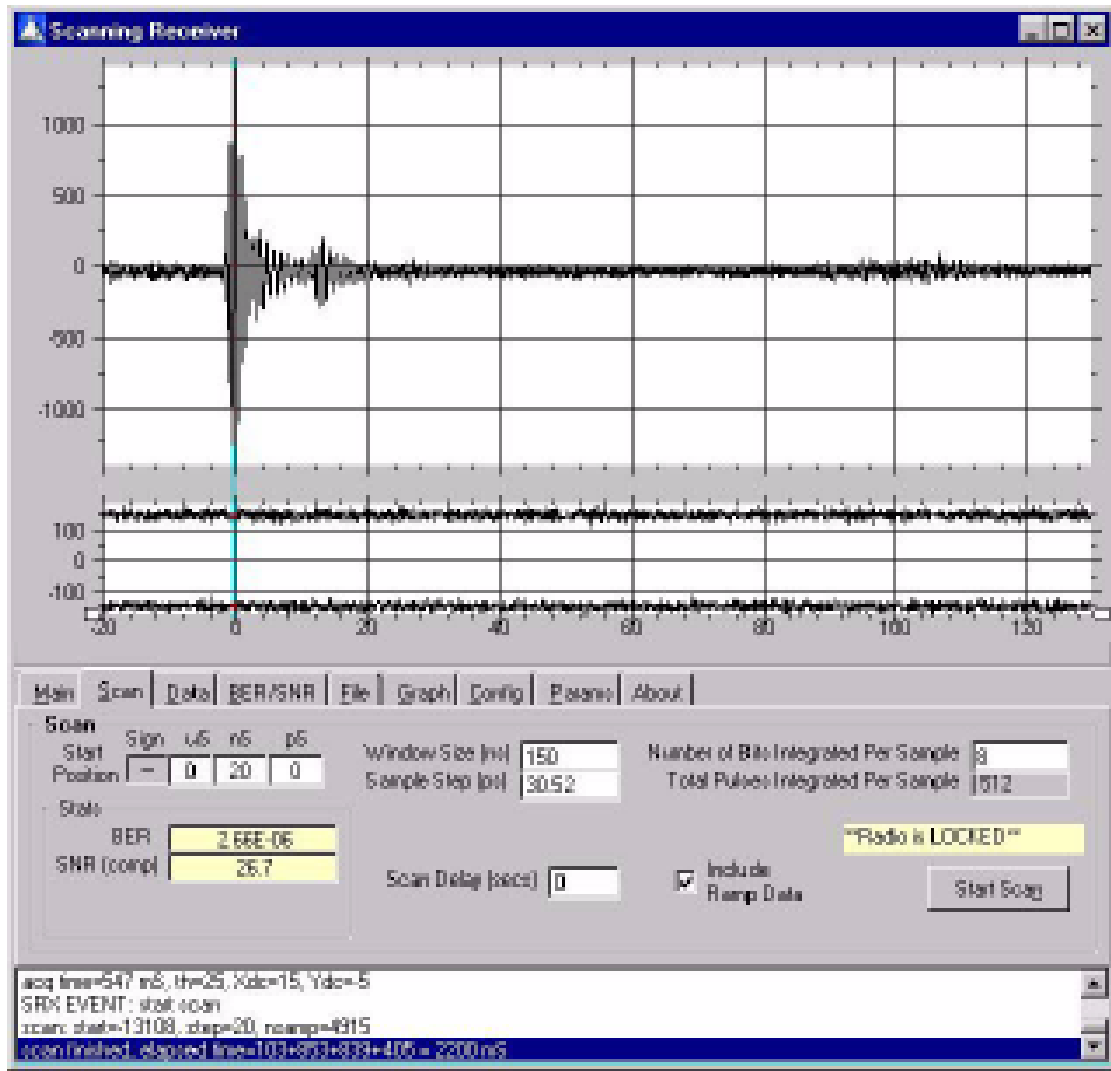
Figure 25 Radio Controller Screen Shot

The receiver has a built in variable gain amplifier (VGA). The values 800 to FFF are written to a 12-bit register to set the gain, with FFF selecting the highest gain. If the receiving PAD cannot acquire a weak signal, increasing the VGA can often help. However, increasing the VGA amplifies the noise as well as the signal, so the FFF setting may not be the best setting in all situations. Placing the receiver and the transmitter 12 feet apart resulted in an SNR value around 40dB. Selecting the BER/SNR Tab in the Radio Controller interface and clicking the "Relock" (even while SNR is around 40dB)

made the Comp (SNR) "0dB" most of the time, but even in this situation the receiver showed "Radio is Locked" and the scan operation could not be completed. The measurement results were neither meaningful nor stable over the test time. It was thought that the SNR value of 40dB was too high for proper operation, which suggests that the transmitter was overdriving the receiver. To prevent the receiver's from being overdriven attenuation was removed from the interference source and the distance between the two PADs was increased. It was determined that 25dB was the optimum SNR value required for successful operations.

It was also noted that receiver radio compression occurs most often when the transmitter and receiver are relatively close together, where path loss is not a significant attenuator of the transmitted signal. Signs indicating radio compression on the PAD unit were as follows:

1. The received Composite SNR was greater than 30 dB.

2. The vertical scale was greater than 2000.

3. The correlation sidelobes (energy occurring every 100 ns) appear large compared to the lock point. This signifies that the receiver has locked onto one of these sidelobes.

4. Upon increasing or decreasing the VGA, the received SNR does not move.

The easiest method to check that the radio is not in compression is by using the 4th sign from above and simply increasing/decreasing the VGA gain to a few different settings: for example, if the SNR increases/decreases accordingly, the radio is NOT in compression. If it does not, however, this is an indication that it is in compression. Another method is to look at the vertical numbers on the scanned waveform on the scan

tab of the receiver software. When recoding data, it is usually best to keep the vertical units between 1000 and 2000. If the vertical number is over 2000, attenuation is required and if the vertical number drops below 1000 attenuation should be removed. Measurements have shown that for optimal radio performance, a target Composite SNR for the receiver should be ~20 dB. A simple method for avoiding radio compression for a given test setup is by:

1. Increasing the distance between the transmitter and receiver.

2. Decreasing the distance between the interference signals antenna and the PADs.

3. Removing the attenuation placed between the signal generator and its antenna.

By removing attenuation, the transmitted signal is attenuated enough so that it does not drive the receiver into a compressed state. The measurements strategy then is to simply add/remove attenuation as needed to improve the measurements (for example, the attenuation is changed as the transmitter and receiver are separated) in order to keep the radio operating in approximately the 20 dB Composite SNR.

Additionally, instead of placing the attenuation between the signal generator and its antenna, the other possible locations could be:

1. On the transmitter

2. On the receiver (between the antenna and the external LNA)

3. On the receiver (between the external LNA and the PAD)

In both locations 1 and 2 adding/removing attenuation changes the signal level but not the noise floor; this results in different SNR values that are dependent on how much attenuation exists in the line. A simple scaling of the received waveform data (based on amount of attenuation) will scale both the signal and noise together; the two cannot be

easily uncoupled.   This means that if attenuation is varied over the course of a measurement in either location 1 or 2 the SNRs recorded will be dependent on the amount of variable attenuation and reflect improper performance.   However, adding/removing the attenuation in location 3 behind the LNA in the receiver chain causes both signal and noise level to move together.   Thus SNRs will not be dependent on the amount of attenuation in this location.

Before beginning any experiment, the SNR value was set around 20dB by using the attenuator, which controlled the strength of the interference source.

4.3.1   CRITICAL SNR VALUES

For several days, at different times of the day, many experiments were conducted to determine the BER versus SNR characteristics.   The experiments mostly focused on finding the unlocked SNR value.   A value of 6.0 dB was the poorest SNR observed during the experiments that could maintain signal reception.   Below 6.0 dB, no signal reception was recorded.   However, additional testing showed that in some tests the poorest SNR that could maintain the reception was no less than 10dB.   Figure 26 shows the different BER-SNR curves for the different days.
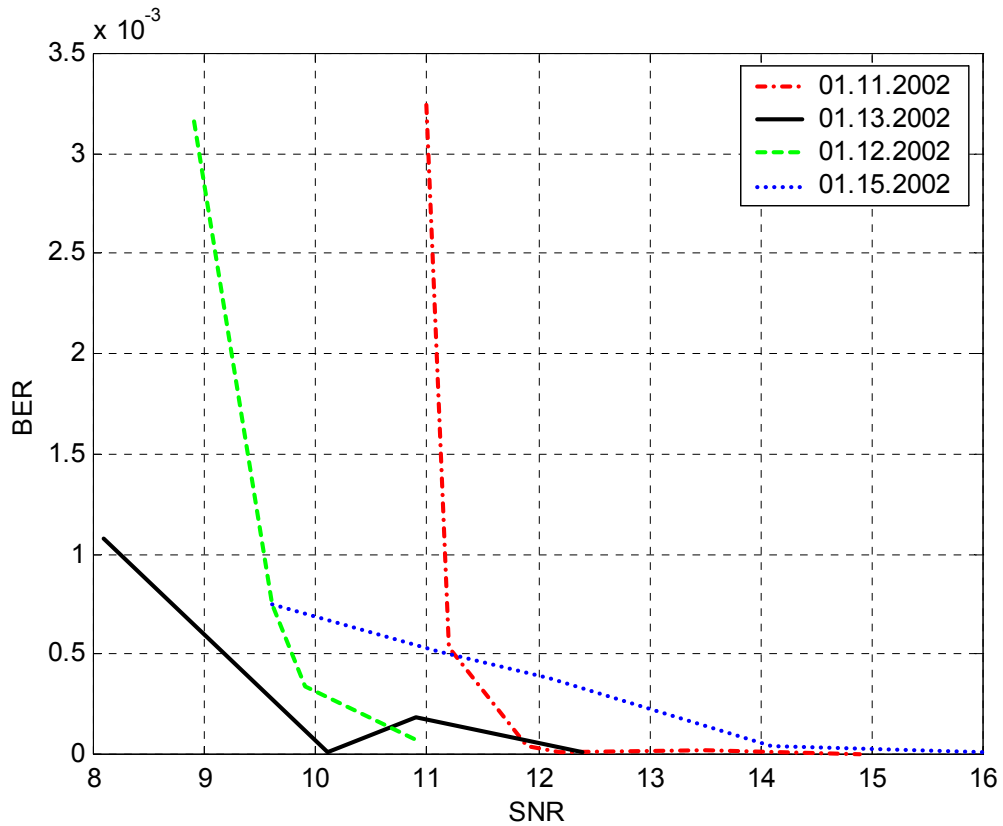
Figure 26 Ber vs. SNR

4.3.2 INTERFERENCE RESULTS

Figure 27 shows the low-noise amplifier input/output. Both LNA input/output are actually high-pass noise filters. They do not have any dB gain but rather eliminate noise to achieve a clean signal.
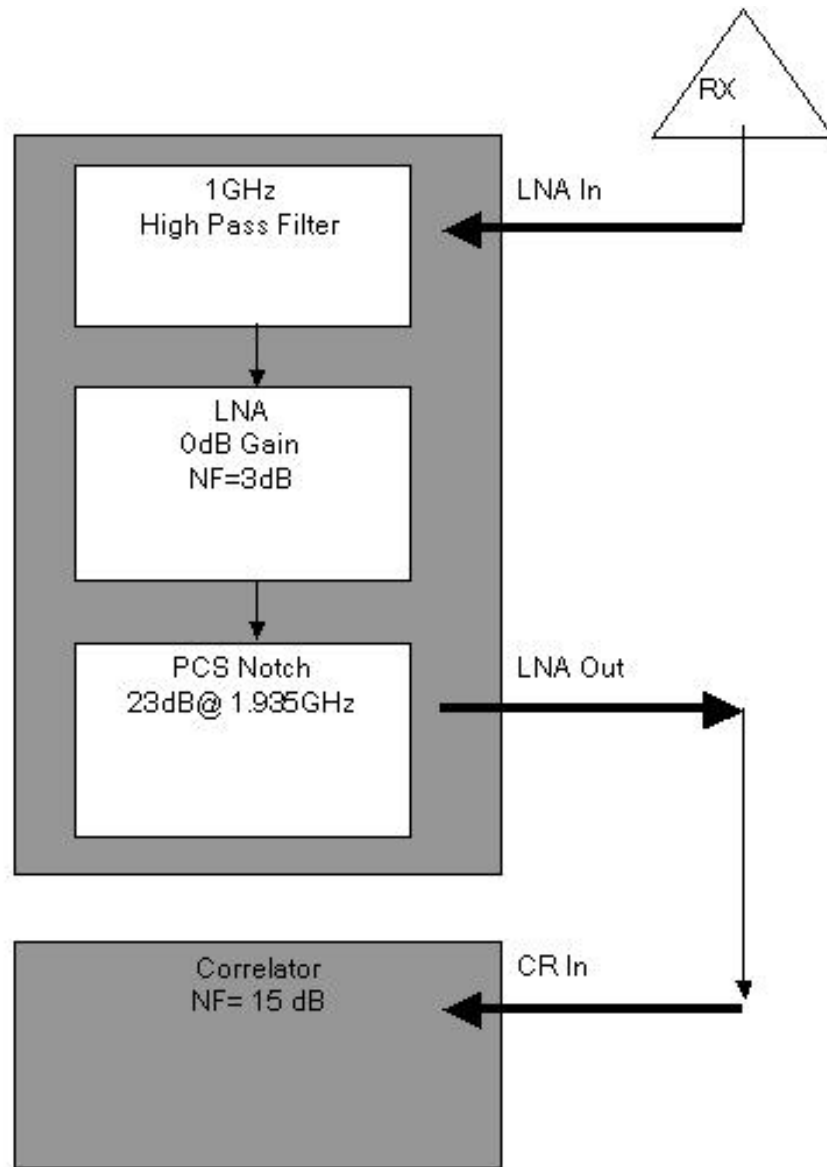
Figure 27 LNA Input/Output

Interference signals with a frequency below 1 GHz or above 5 GHz cannot cause any aggregate effects on the reception, due to the characteristics of the LNA. After various experiments it was found that the system's most sensitive frequency was around 2.109GHz. This sensitive frequency was determined at the several iterations. The interference source was generated from 1 GHz and increased gradually. Starting from 1.9 GHz, the effect of the interference was seen as an increase in the SNR value. At this point

increasing steps were narrowed. It was noted that the interference frequency at around 2.1 GHz stopped the reception. Thus, the major interference sources of interest to this research (which were simulated using a signal generator), were well below the 2.1GHz threshold. The signal generator antenna was placed 25 cm away from the receiver antenna. The SNR metric and BER tab value were recorded during each experiment. The tested interference signals were unable to unlock the signal's reception or produce any BER. The minimum recorded SNR was around 18dB, which was good enough to maintain accurate signal reception with a zero BER.

4.4   *RADIATED MEASUREMENTS RESULTS FOR WLAN*

Two different wireless communication methods between the PADs were evaluated for data modulation/demodulation and real time processing capability, Microsoft® NetMeeting® and a UWB network.

The major disadvantage with Microsoft® NetMeeting® was that the data could only be received as an image and therefore could not be processed in real time.

The UWB network's main advantage was that the data could be received and processed in real time, therefore the UWB network setup was much more practical and convenient for this research. An experiment was setup to determine the UWB network's performance using an Xpod® evaluation kit. Physiological data produced by the Xpod® was modulated continuously onto the UWB signal. The received data was processed with Matlab® code and displayed in real time. This experiment demonstrated the feasibility in using PADs as a data communications system for firefighters inside and outside of buildings. The major factor affecting the transmission BER performance was the protocol type, TCP/IP.

4.4.1 BER vs. SNR PERFORMANCE

In this test phase, the interference signals shown in Table 2 were used as the interference sources. Since the PADs use TCP/IP, no BER was detected. As a result either the transmission was done without error or it was terminated. Recall, that the TCP uses packet cyclic redundancy check and resends (backward error correction), and that's why there are never any errors in the file. As SNR is reduced, the TCP protocol timeouts long before the BER gets high enough to make an error in the file. None of the tested interference sources were able to terminate the Xpod®'s data transmission. Figure 28 shows the XPOD output.
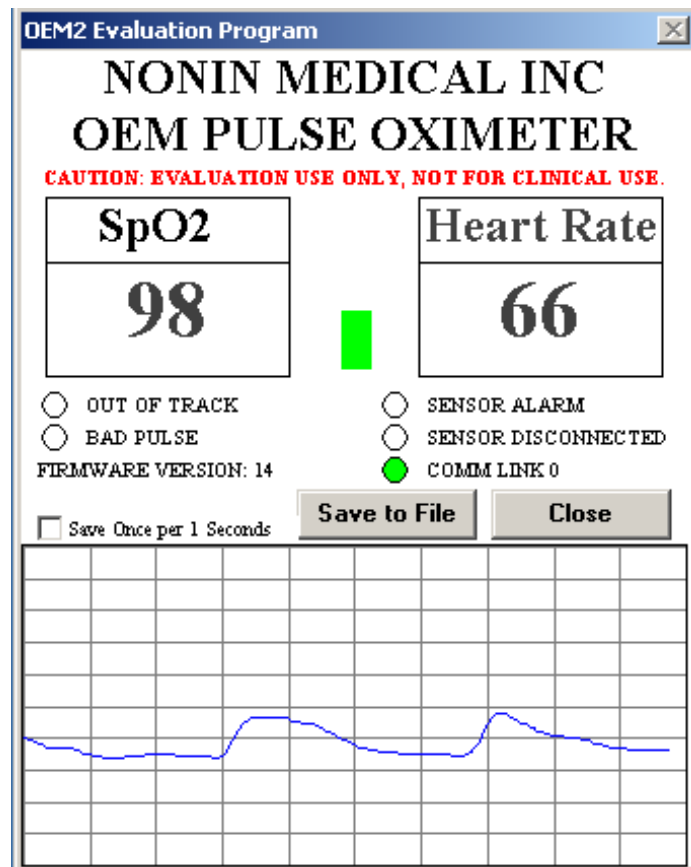

Figure 28 Xpod® Output

Figure 29 shows the received data.
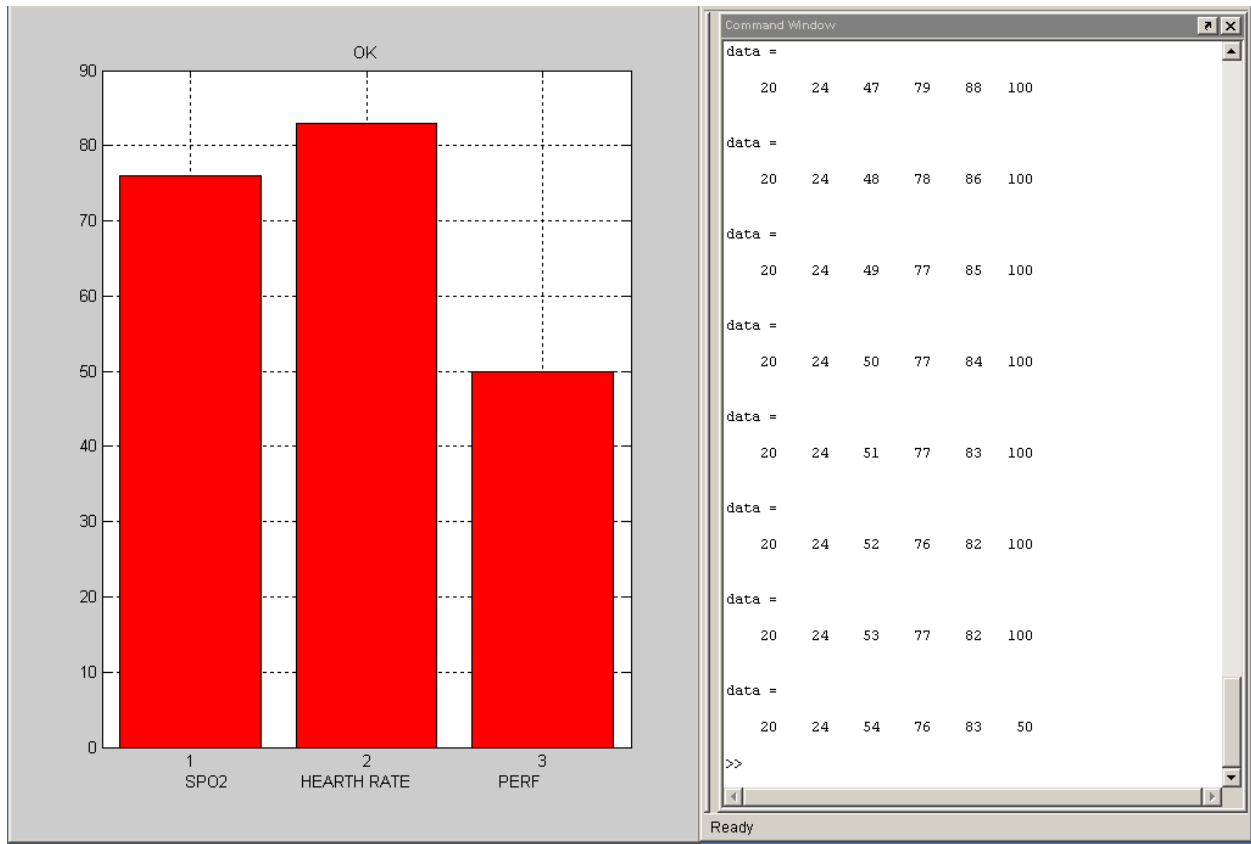
Figure 29 Received Physiological Data

V. CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

The first step in this research was to find a possible solution for indoor geolocation based on electromagnetic radiation technology. UWB technology, the promising solution to many propagation problems encountered in indoor environments was chosen as the research topic. The basic concept involved in UWB technology is to develop, transmit and receive an extremely short duration burst of RF energy, typically tens of picoseconds (trillionths of a second) to a few nanoseconds (billionths of a second) in duration. The primary UWB advantage rests in its ability to spread the signal's energy and the spectrum across the signal's wide bandwidth.

Since UWB technology has the ability to fuse wireless communication, tracking, and radar capabilities, it offers wide array of applications including wireless networks, public safety applications involving motion detection through walls or rubble, personnel and asset tracking in-building, invisible security domes and fences, and ultra high precision positioning/tracking systems [8].

The TM-UWB PAD was the primary hardware utilized to test the UWB technology performance for several applications in different environments. These PADs have been developed by Time Domain Corporation based upon the TM-UWB architecture.

5.2   CONCLUSIONS

The Scanning Receiver, WLAN and PLT applications were analyzed under different interference environments applicable to the expected operational scenarios for a personnel positioning and physiological monitoring system.   In each case, the interference signals were not able to cause the UWB signal to unlock the PADs.

Users can avoid interference between numerous UWB systems operating in close proximity by communicating using a unique timing code. In addition, using time coding and pulse integration results in robust operation in noisy radio environments. Integration has helps since it overcomes noise and interference.

A major benefit to the UWB technology is that the PADs operate at very low power emission levels, and can transmit/receive/process in cluttered environments extremely well. As a result PAD technology can provide wireless solutions for indoor environments.

In addition, another benefit relates to Rayleigh, or multipath fading, which adversely affects continuous wave system. Fading inevitably occurs when continuous sine waves are transmitted inside buildings, i.e., signals reflect off objects and suffer destructive cancellation and constructive addition. UWB technology is not based on continuous wave technology so is not affected negatively by this phenomenon.

A typical user UWB application involves a fire department responding to a burning building. Using a UWB-based personnel positioning and physiological monitoring system, firefighters who enter the burning building could be continuously tracked in real-time through the smoke and walls allowing a person monitoring the

situation outside of the building to assess the situation and act quickly if the firefighters in the building become lost or trapped.

This is critical, since today's GPS-based systems do not work well or at all in urban or closed-door environments where obstructions such as buildings, walls and trees interrupt the receiver-to-satellite's line-of-sight communication. Communication (or ranging) is dependent on the material through which you are transmitting, your data rate, and your transmitting power.

Currently, multipath is the major enemy to present RF solutions. The echo effect makes ranging practically impossible, as the receiver cannot distinguish the direct transmission path from the multipath resulting in erroneous data. However newly developed algorithms allow the multipath to help strengthen the overall signal by locking on to a point on the signal, be it the direct path or the multipath, and locate the leading edge (or direct path) [6]

Current systems have limited accuracy. Known indoor systems have attained an accuracy of 10-20 feet (3-6meters) in a 2D environment. While that may work well to track an object from one flight hanger to another, it does not work well in the typical office layout where the average office is approximately 10-feet by 10-feet (3-meters by 3-meters) or warehouses where pallets measure 3-feet by 3-feet (0.3-meter by 0.3 meters). PLT tracking demonstrations have shown an average accuracy in the six inch or better range in both 2Dand 3D environments permitting full 3D.

In addition, current RF tracking systems are sensitive to interference from cell phones, pagers, 802.11 and Bluetooth devices. Equally limiting are government and safety restrictions placed on the wireless devices. For example, only limited RF levels

are allowed near military munitions stores. Hospitals require individuals to turn off their cell phones before entering the premises.

Another UWB-based system benefit over current tracking systems, such as GPS, is its ability to simultaneously communicate in addition to tracking. While GPS-based tracking systems can track an object, they cannot send or receive data packets using the GPS signal – an additional transceiver communication system would be required. Therefore, the UWB-based PLT allows for simultaneous location tracking and communication even in indoors.

Also, current systems require an expensive wired infrastructure for 2D tracking reference beacons to communicate and synchronize with each other. The UWB-based PLT architecture needs only a minimum of three reference beacons operating independently with no wires needed for communication or synchronization.

Finally, UWB-based technology alleviates the concerns associated with the varying spectrum restrictions, which exist across international borders. A problem exists since a non-interfering radio in one country becomes a jammer in another. With the UWB-based PADs, spectrum restrictions are not an issue as UWB spans the spectrum but in the noise floor where spectrum issues are non-existent.

5.3   RECOMMENDATIONS FOR FURTHER RESEARCH

This thesis research provided an insight and baseline performance capability associated with the UWB-based PAD technology. It also investigated the effect of selected inference signals on the PAD's performance. Due to limited research time, the PLT application was not adequately analyzed to evaluate its capabilities. This would be the next step for future work. Additional recommendations the followings:

Integrating physiological sensors with the PAD's PLT application, which is known to have the capability to produce accurate geolocation information and the ability to modulate any data type. This system should then be analyzed in real-world scenarios.

Conduct a detailed comparison between PAD performance and other wideband radio systems and narrowband systems in terms of their ability to transmit data and accomplish PLT.

Conduct a thorough investigation in the ability of UWB devices to coexist with existing wireless systems.

Investigate the various UWB signaling formats in relation to the regulatory constraints.

Analyze UWB coding and error correction strategies and antenna technology.

Compare the performance and the complexity tradeoffs between systems based on TM-UWB and narrow band radio systems based on coded orthogonal frequency division multiplexing. The comparison topics could be:

1. Spreading efficiency.
2. Power spectral density.
3. Robustness against multipath effects.
4. Localization and positioning capabilities.

Incorporate UWB devices with multiple parallel receivers, known as RAKE receiver architecture, to coherently add the energy from the many suitable reflected signals to increase the signal-to-noise ratio. It is suggested that in an indoor environment rake architecture can significantly improve performance.

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1. REPORT DATE *(DD-MM-YYYY)* 12-03-2002	**2. REPORT TYPE** **Master's Thesis**	**3. DATES COVERED** *(From – To)* Jun 2001 – Mar 2002

4. TITLE AND SUBTITLE ULTRA WIDE BAND (UWB) TECHNOLOGY FOR AN FOR INDOOR GEOLOCATION AND PHYSIOLOGICAL MONITORING SYSTEM	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Cegiz Alabacak, 1st Lt, TUAF	**5d. PROJECT NUMBER** If funded, enter ENR #
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 P Street, Building 640 WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GE/ENG/02-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) DARPA Special Project Office Lt. Col. Gregory Vansuch 3701 N. Fairfax Drive DSN: 7030248 Arlington VA 22203-1714	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The goal of this research is to analyze the utility of UWB for indoor geolocation and to evaluate a prototype system, which will send information detailing a person's position and physiological status to a command center. In a real world environment, geolocation and physiological status information needs to be sent to a command and control center that may be located several miles away from the operational environment. This research analyzes and characterizes the UWB signal in the various operational environments associated with indoor geolocation. Additionally, "typical usage scenarios" for the interaction between UWB and other devices are also tested and evaluated.

15. SUBJECT TERMS
Ultra Wide band
Pulse Position Modulation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Mikel M. Miller, Lt. Col, USAF (ENg)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	**UU**	90	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565, ext. 4278; e-mail: mikel.miller@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18